



Calhoun: The NPS Institutional Archive
DSpace Repository

Theses and Dissertations

1. Thesis and Dissertation Collection, all items

2021-06

HYDROGEN FUEL OPERATION FOR GAS TURBINE ENGINES

Hardt, Ethan J.

Monterey, CA; Naval Postgraduate School

<http://hdl.handle.net/10945/67731>

This publication is a work of the U.S. Government as defined in Title 17, United States Code, Section 101. Copyright protection is not available for this work in the United States.

Downloaded from NPS Archive: Calhoun



<http://www.nps.edu/library>

Calhoun is the Naval Postgraduate School's public access digital repository for research materials and institutional publications created by the NPS community. Calhoun is named for Professor of Mathematics Guy K. Calhoun, NPS's first appointed -- and published -- scholarly author.

Dudley Knox Library / Naval Postgraduate School
411 Dyer Road / 1 University Circle
Monterey, California USA 93943



NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

HYDROGEN FUEL OPERATION FOR GAS TURBINE ENGINES

by

Ethan J. Hardt

June 2021

Thesis Advisor:
Co-Advisor:
Second Reader:

Anthony J. Gannon
Garth V. Hobson
Walter Smith

Approved for public release. Distribution is unlimited.

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE			<i>Form Approved OMB No. 0704-0188</i>	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE June 2021	3. REPORT TYPE AND DATES COVERED Master's thesis		
4. TITLE AND SUBTITLE HYDROGEN FUEL OPERATION FOR GAS TURBINE ENGINES			5. FUNDING NUMBERS RMNPB	
6. AUTHOR(S) Ethan J. Hardt				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Office of Naval Research, Arlington, Virginia.			10. SPONSORING / MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.				
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release. Distribution is unlimited.			12b. DISTRIBUTION CODE A	
13. ABSTRACT (maximum 200 words) The purpose of this thesis was to operate a gas turbine engine on hydrogen fuel at near full load. Hydrogen fuel is sought after by the Department of the Navy due to its ability to increase energy security and energy independence to naval forces. The two engines researched were the C30 Capstone microturbine and JetCat P60 turbine. The Capstone C30 was experimentally run with hydrogen fuel and these results are compared to propane fuel data at varying loads. The JetCat P60 was simulated using a hydrogen fuel source. These simulations aid in potential engine modifications to ensure safe operation for future experimental work. Recommendations to produce a fully operational hydrogen supply system are discussed as well as to operate the C30 at full power.				
14. SUBJECT TERMS hydrogen, micro turbine, energy, renewable energy			15. NUMBER OF PAGES 99	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT UU	

THIS PAGE INTENTIONALLY LEFT BLANK

Approved for public release. Distribution is unlimited.

HYDROGEN FUEL OPERATION FOR GAS TURBINE ENGINES

Ethan J. Hardt
Ensign, United States Navy
BS, United States Naval Academy, 2020

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

from the

**NAVAL POSTGRADUATE SCHOOL
June 2021**

Approved by: Anthony J. Gannon
Advisor

Garth V. Hobson
Co-Advisor

Walter Smith
Second Reader

Garth V. Hobson
Chair, Department of Mechanical and Aerospace Engineering

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

The purpose of this thesis was to operate a gas turbine engine on hydrogen fuel at near full load. Hydrogen fuel is sought after by the Department of the Navy due to its ability to increase energy security and energy independence to naval forces. The two engines researched were the C30 Capstone microturbine and JetCat P60 turbine. The Capstone C30 was experimentally run with hydrogen fuel and these results are compared to propane fuel data at varying loads. The JetCat P60 was simulated using a hydrogen fuel source. These simulations aid in potential engine modifications to ensure safe operation for future experimental work. Recommendations to produce a fully operational hydrogen supply system are discussed as well as to operate the C30 at full power.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

I.	INTRODUCTION.....	1
A.	MOTIVATION	1
B.	LITERATURE REVIEW	2
C.	PREVIOUS WORK.....	4
D.	APPROACH.....	6
II.	C30 DESIGN MODIFICATIONS.....	7
A.	CAPSTONE COMBUSTION CHAMBER	8
B.	ADDITIONAL TESTING EQUIPMENT	10
C.	PROPOSED FUTURE SUPPLY DESIGN	10
III.	OPERATION OF C30 CAPSTONE	13
A.	RESULTS AND ANALYSIS	13
1.	Propane Fuel.....	14
2.	Hydrogen Fuel.....	16
B.	GASTURB COMPARISON	18
C.	DISCUSSION AND RECOMMENDATIONS.....	20
IV.	JETCAT SIMULATIONS	23
A.	MODELING.....	23
B.	SETUP.....	26
C.	HYDROGEN-AIR COMBUSTION RESULTS AND ANALYSIS	28
D.	DISCUSSION AND RECOMMENDATIONS.....	33
V.	CONCLUSIONS AND FUTURE WORK.....	35
A.	C30 CAPSTONE	35
B.	JETCAT	35
	APPENDIX A. PROCEDURE FOR OPERATION WITH HYDROGEN	37
	APPENDIX B. C30 GASTURB INPUTS AND OUTPUTS.....	41
A.	PROPANE INPUTS.....	41
B.	PROPANE OUTPUTS	44
C.	HYDROGEN INPUTS	48
D.	HYDROGEN OUTPUTS	51

APPENDIX C. C30 HYDROGEN FUEL MASS FLOW CALCULATIONS	55
APPENDIX D. JETCAT GASTURB INPUTS AND OUTPUTS.....	57
A. PROPANE INPUTS.....	57
B. PROPANE OUTPUTS	60
C. HYDROGEN INPUTS	63
D. HYROGEN OUTPUTS.....	66
APPENDIX E. JETCAT BOUNDARY CONDITIONS	69
APPENDIX F. JETCAT CFX RESIDUALS.....	73
LIST OF REFERENCES	77
INITIAL DISTRIBUTION LIST	79

LIST OF FIGURES

Figure 1.	Comparison of gravimetric density and volumetric density based on LHV	3
Figure 2.	C30 Capstone test results for engine speed and TET for different fuel sources. Source: [6].....	5
Figure 3.	Propane and hydrogen fuel supply systems	7
Figure 4.	Conex box for C30 and fuel supply system.....	8
Figure 5.	Original combustion chamber with pre-mix tubes.....	9
Figure 6.	Combustion chamber without pre-mix tubes and capped fittings.	9
Figure 7.	Load bank and end connection to C30.....	10
Figure 8.	Updated hydrogen supply system/design.....	11
Figure 9.	Engine Speed versus time for varying load propane fuel	14
Figure 10.	Turbine exit temperature versus time for varying load propane fuel.....	15
Figure 11.	Engine Speed versus time for varying load hydrogen fuel	16
Figure 12.	Turbine exit temperature versus time for varying load hydrogen fuel	17
Figure 13.	Comparison of GASTURB and experimental turbine exit temperature at different loads for propane fuel.....	19
Figure 14.	Comparison of GASTURB and experimental turbine exit temperature at different loads for hydrogen fuel	19
Figure 15.	Combustion chamber model (left) and actual JetCat combustion chamber (right).....	23
Figure 16.	60° combustion chamber cover with fuel inlet	24
Figure 17.	Sliced geometry used in CFX analysis	25
Figure 18.	Mesh generated in CFX analysis	26
Figure 19.	JetCat boundary locations	27
Figure 20.	Momentum and mass residuals for hydrogen combustion CFX.....	28

Figure 21.	Heat addition throughout the combustion process.....	29
Figure 22.	Hydrogen flame development at 1000 iterations	30
Figure 23.	Hydrogen flame development at 3000 iterations	30
Figure 24.	Hydrogen flame development at 7000 iterations	31
Figure 25.	Hydrogen flame development at 11000 iterations	31
Figure 26.	Combustion chamber outlet temperature at 11000 iterations	32
Figure 27.	C30 basic data inputs (generic/propane).....	41
Figure 28.	C30 heat exchanger data inputs (generic/propane).....	41
Figure 29.	C30 air system data inputs (generic/propane).....	42
Figure 30.	C30 compressor efficiency data inputs (generic/propane).....	42
Figure 31.	C30 compressor design data inputs (generic/propane)	43
Figure 32.	C30 turbine efficiency data inputs (generic/propane).....	43
Figure 33.	C30 summary of outputs (generic/propane)	44
Figure 34.	C30 compressor data outputs (generic/propane).....	45
Figure 35.	C30 air system outputs (generic/propane)	46
Figure 36.	C30 enthalpy-entropy diagram (generic/propane)	47
Figure 37.	C30 temperature-entropy diagram(generic/propane).....	48
Figure 38.	C30 basic data inputs (hydrogen)	48
Figure 39.	C30 heat exchanger inputs (hydrogen)	49
Figure 40.	C30 air system inputs (hydrogen)	49
Figure 41.	C30 compressor efficiency inputs (hydrogen).....	50
Figure 42.	C30 compressor design inputs (hydrogen)	50
Figure 43.	C30 turbine efficiency inputs (hydrogen)	50
Figure 44.	C30 summary of outputs (hydrogen)	51
Figure 45.	C30 compressor data outputs (hydrogen)	52

Figure 46.	C30 air system outputs (hydrogen)	53
Figure 47.	C30 enthalpy-entropy diagram (hydrogen).....	54
Figure 48.	C30 temperature-entropy diagram (hydrogen)	54
Figure 49.	JetCat basic data (generic/propane)	57
Figure 50.	JetCat nozzle selection (generic/propane)	57
Figure 51.	JetCat reheat (generic/propane)	58
Figure 52.	JetCat compressor design (generic/propane)	59
Figure 53.	JetCat compressor efficiency (generic/propane).....	59
Figure 54.	JetCat turbine efficiency (generic/propane).....	59
Figure 55.	JetCat summary of outputs (generic/propane)	60
Figure 56.	JetCat air system outputs (generic/propane)	61
Figure 57.	JetCat enthalpy-entropy diagram (generic/propane).....	62
Figure 58.	JetCat temperature-entropy diagram (generic/propane)	62
Figure 59.	JetCat basic data (hydrogen).....	63
Figure 60.	JetCat nozzle selection (hydrogen)	63
Figure 61.	JetCat air system (hydrogen)	64
Figure 62.	JetCat reheat (hydrogen)	64
Figure 63.	JetCat compressor design (hydrogen).....	65
Figure 64.	JetCat compressor efficiency (hydrogen)	65
Figure 65.	JetCat turbine efficiency (hydrogen)	65
Figure 66.	JetCat summary of outputs (hydrogen).....	66
Figure 67.	JetCat air system outputs (hydrogen).....	67
Figure 68.	JetCat enthalpy-entropy diagram (hydrogen)	68
Figure 69.	JetCat temperature-entropy diagram (hydrogen)	68
Figure 70.	JetCat heat transfer residual	73

Figure 71.	JetCat turbulence residuals	74
Figure 72.	JetCat mass fractions residuals	75

LIST OF TABLES

Table 1.	C30 test results for idle operation	13
Table 2.	C30 test results for propane variable loads	15
Table 3.	C30 test results for hydrogen variable loads.....	17
Table 4.	Power specific fuel consumption for C30.....	20
Table 5.	Thrust specific fuel consumption for JetCat engine at max power.....	33
Table 6.	JetCat default domain setup	69
Table 7.	JetCat inlet boundary conditions.....	70
Table 8.	JetCat fuel inlet boundary conditions	70
Table 9.	JetCat outlet boundary conditions.....	71
Table 10.	JetCat domain interface boundary conditions.....	71

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF ACRONYMS AND ABBREVIATIONS

C30	Capstone Turbine Corporation C30 Microturbine
CFD	computational fluid dynamics
DOD	Department of Defense
DON	Department of the Navy
FOD	foreign object debris
HAZ	heat affected zone
K	Kelvin
kN	kilonewton
kPa	kilopascal
kW	kilowatts
m/s	meters per second
PSFC	power specific fuel consumption
RPM	revolutions per minute
s	seconds
TET	turbine exit temperature
TSFC	thrust specific fuel consumption

THIS PAGE INTENTIONALLY LEFT BLANK

ACKNOWLEDGMENTS

I would like to thank my family and friends for their support during my studies at NPS and USNA. I would like to thank USNA professors, LCDR Ethan Lust and Professor Patrick Caton, for mentorship and encouragement to continue my education at NPS.

I would like to thank Dr. Anthony Gannon and Dr. Garth Hobson for the vision of this hydrogen project. Dr. Walter Smith for teaching me about the operation of the C30 system, and lastly, Mr. John Gibson for technical support while working with the engines.

THIS PAGE IS INTENTIONALLY LEFT BLANK

I. INTRODUCTION

The purpose of this research is to extend the work of developing hydrogen-fueled gas turbine engines. Hydrogen engines have potential to revolutionize the renewable energy needs of the Department of the Navy (DON). This work is sponsored by the Office of Naval Research. The objectives of this research are to reconfigure a Capstone Turbine Corporation C30 Microturbine (C30) for hydrogen operation, evaluate parameters affected by different sources of fuel, and model hydrogen fuel combustion in a JetCat P60 engine.

A. MOTIVATION

Renewable energy is one of the fastest growing energy sources globally. Private businesses and federal governments are developing new technology in order to gain energy independence from oil and natural gas. Within the U.S. federal government, the DON is a front runner in researching renewable energy. One reason is because over 80 percent of the federal government's energy consumption occurs within the DON [1]. The DON also has two major energy goals: energy security and energy independence [2]. Energy security is "the ability to protect and deliver sufficient energy to meet all operational needs" [2]. Energy independence is relying only on energy sources that can withstand accidental or intentional disruptions. It also "increases operational effectiveness by making Naval forces more *energy self-sufficient* and less dependent on vulnerable energy production and supply lines" (emphasis added) [2].

Along with the DON search for a renewable energy strategy, the Department of Defense (DOD) is looking for a solution to counter attacks on energy logistics. "Between Oct 2001 and Dec 2010, 52% of Operation Enduring Freedom and Operation Iraqi Freedom casualties occurred from hostile attacks during land transport missions" [3]. The DON has also encountered casualties with refueling like the attack on the USS Cole. The DOD and DON want a fuel source that lasts longer and can be produced through renewable energy.

The fuel source of interest is hydrogen. Hydrogen combustion in air is similar to typical hydrocarbons used in gas powered turbines. Unlike propane and methane, which

produce carbon dioxide in reactions with air, hydrogen primarily produces water and little or no carbon dioxide. A hydrogen and air reaction is a carbon free reaction desired for the DON renewable energy initiative.

B. LITERATURE REVIEW

Hydrogen is a unique fuel source because of its extremely high gravimetric density compared to other fuels such as methane and JP-8. Combined with being the most abundant and simplest element, the small and light molecular structure has potential to be the future of renewable energy.

The primary way to produce hydrogen is through gasification. Breaking hydrocarbon bonds allows for hydrogen to be extracted in large quantities for reasonable costs and high efficiency. Issues occur in the byproducts of this process by omitting CO and CO₂ [4]. An alternative way to produce hydrogen is electrolysis. Electrolysis is used to separate water into hydrogen and oxygen. Once separated, hydrogen is then compressed and stored. The small process means it can be applied practically anywhere around the world since only electricity and water is required. While the process is easy to apply, high production costs due to low conversion efficiency and electrical power are major drawbacks to large scale production [5]. However, combined with emission free electricity, such as wind, solar, or geothermal power, hydrogen can become a renewable fuel cell.

The difficulty in using hydrogen comes from the low volumetric density. Figure 1 is a comparison of gravimetric and volumetric density of different fuels.

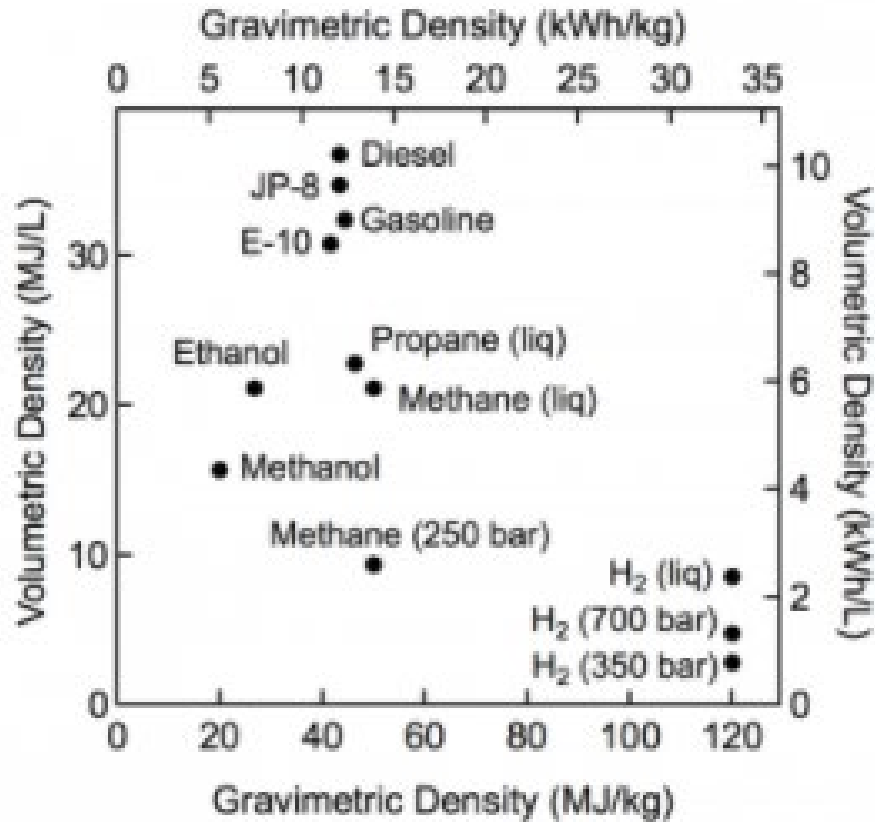


Figure 1. Comparison of gravimetric density and volumetric density based on LHV

Hydrogen at ambient pressure only has 0.0107 MJ/L, which is three times smaller than methane and almost 2500 times smaller than liquid propane [5]. The low volumetric density has often been the reason hydrogen was avoided as an alternative fuel.

Another issue which arises is the compression and storage of hydrogen. Currently, hydrogen is compressed into high pressure vessels. The main problem with this approach is hydrogen's low storage density [5]. The low storage density requires hydrogen fuel to be stored in large, high pressure canisters compared to methane and propane fuel tanks. There will be difficulty in overcoming the storage problem of hydrogen, but these problems can be overcome with recent renewed interest in hydrogen.

C. PREVIOUS WORK

Kaufmann [6] worked with the Capstone C30 Microturbine. Kaufmann modeled CFD combustion, but only for a general combustion chamber. The three fuels compared were propane, methane, and hydrogen. The findings of this simulation showed that hydrogen had an adiabatic flame temperature almost 400 K higher than propane and methane. This showed that a new hydrogen combustion chamber may have to be created to replace the original propane and methane combustion chamber in order to deal with the higher increase in temperature. Another potential issue with the hydrogen fuel is the ability to supply the required volumetric flow rate. Kaufmann then analyzed the C30 itself. The C30 was run on propane, natural gas, and lastly, hydrogen. Propane and natural gas were able to fully operate the C30 on idle speed. Hydrogen was only able to run on idle speed for a short duration. Kaufmann's test results for engine speed and turbine exit temperature (TET) are shown in Figure 2.

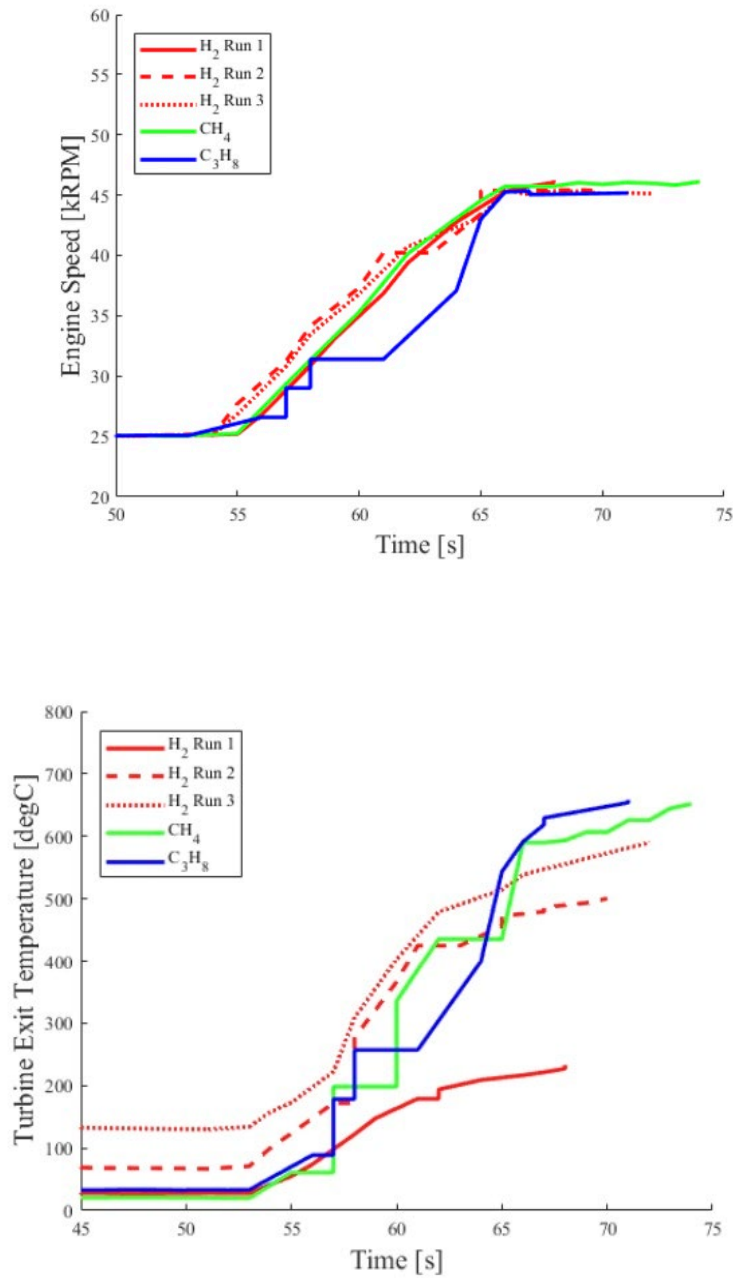


Figure 2. C30 Capstone test results for engine speed and TET for different fuel sources. Source: [6].

Three different runs used hydrogen but at different input pressures. The higher the input pressure increased the run time. One issue noted was the potential choked flow in the hydrogen line to prevent higher pressures from having sustained combustion.

D. APPROACH

This thesis analyzed the use of hydrogen fuel in two different engines. The two engines analyzed were the C30 Capstone and JetCat P60. The C30 Capstone is a larger engine capable of providing 30 kW of power, while the JetCat, a remote control plane turbofan engine, produces around 63 N of thrust. The C30 was chosen as the experimental engine because of its tested ability by its manufacturer to operate on hydrogen fuel [6]. The experimental test compared the use of hydrogen fuel and propane fuel at similar operating conditions. Once the data was captured and processed for a variety of different operating conditions, GASTURB simulations were generated to calculate fuel flow rates and other parameters which were unable to be measured during the experimental testing. The JetCat hydrogen operation is unknown because the engine was designed to burn liquid fuel. The JetCat engine was simulated at operating conditions using computational fluid dynamics (CFD). The simulation was intended to identify areas for combustion chamber modifications for safe and successful experimental research.

Recommendations were made to improve the hydrogen fuel supply line for the C30. JetCat recommendations included different modeling techniques to best model actual combustion within the combustion chamber. Future work can lead to implementation of hydrogen capturing systems to create fuel cells capable of running and refueling the C30 within the same system.

II. C30 DESIGN MODIFICATIONS

Modifications were made to the previous experimental setup of the C30, a 30 kW electrical generating gas turbine. The two primary design modifications were involved with safe operation of the Capstone engine and additional testing equipment for further experimental results. The setup for the propane and hydrogen systems are shown in Figure 3.

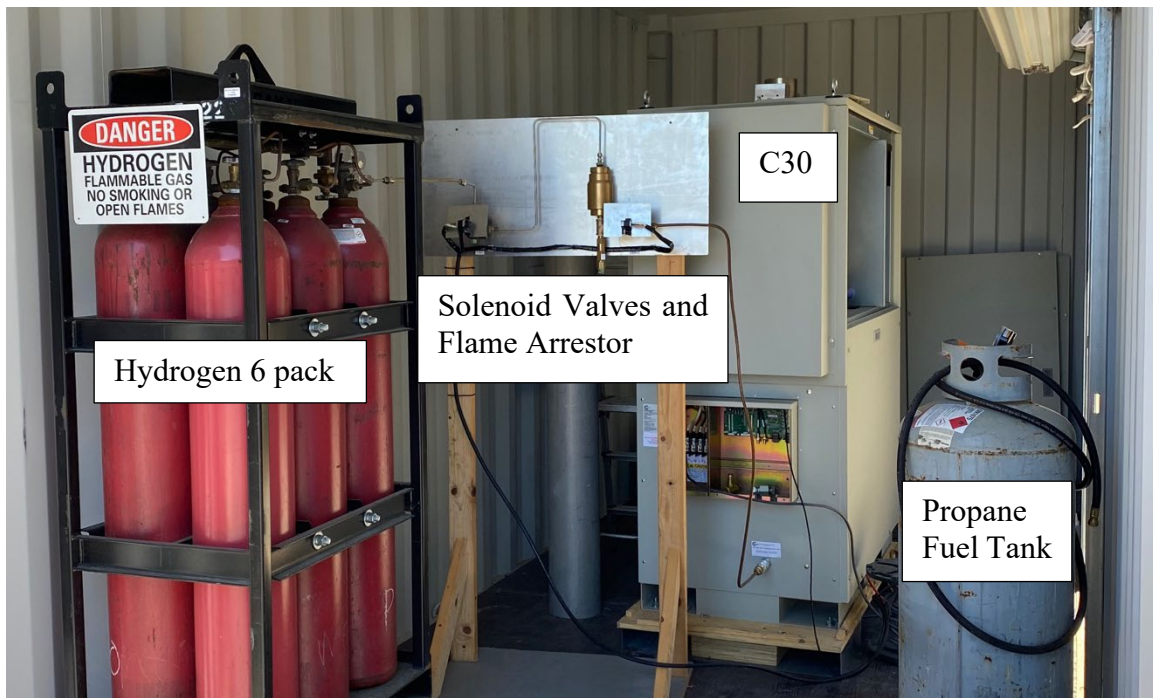


Figure 3. Propane and hydrogen fuel supply systems

The propane system on the right contains a propane filled tank with a regulator and a 9.52 mm flexible fuel line. The hydrogen system on the right contains a 6 pack of fuel tanks with a regulator, two solenoid valves, a flame arrestor, and 6.35 mm fuel tubing. The fuel supply systems and the C30 were all stored in a conex box shown in Figure 4.



Figure 4. Conex box for C30 and fuel supply system

A. CAPSTONE COMBUSTION CHAMBER

Capstone, the engine manufacturer, recommended the removing and capping of three pre-mix injectors from the combustion chamber [7]. The original combustion chamber and the modifications are shown in Figures 5 and 6.

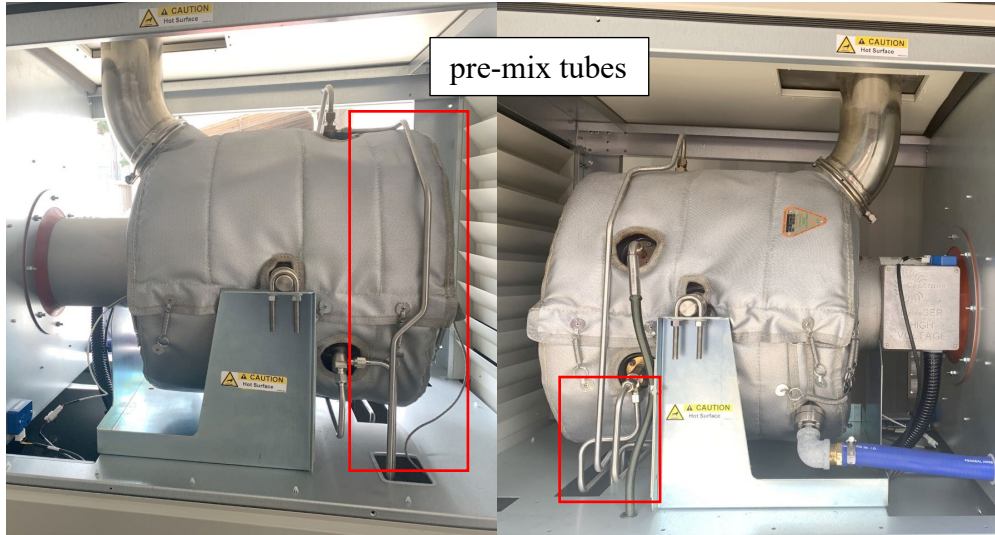


Figure 5. Original combustion chamber with pre-mix tubes.



Figure 6. Combustion chamber without pre-mix tubes and capped fittings.

These injectors were removed to reduce the risk of injector flashback. Flashback is burning in the injector which travels toward the fuel source. The hydrogen's higher flame speed increases the risk of injector flashback within the Capstone engine [7]. Injector flashback has potential to melt the fuel injectors leading to foreign object debris (FOD) to the turbine rotor.

A future design modification would be to place valves at the pre-mix injectors. The purpose of these valves would be to easily switch between a hydrogen and propane fuel source. The pre-mix tubes would also need modifications to fit with the added valves.

B. ADDITIONAL TESTING EQUIPMENT

A Mosebach's X30 load bank was added to the system to test the C30 at full power. The load bank applied loads for different operating conditions of the C30. The C30 was able to record and capture the data from the applied loads. The load bank and its connection to the Capstone engine are shown in Figure 7.



Figure 7. Load bank and end connection to C30.

The load bank allows for loads varying from 1 kW up to 30 kW [8]. The dials contain one 1 kW switch, two 2 kW switches, one 5 kW switch, and two 10 kW switches. The power supply can be easily varied throughout an experimental run to collect data at different output power levels. Turning on all switches represents 30 kW and the maximum power the C30 Capstone can supply. The four connections are applied directly to the Capstone engine along with a ground connection, far left.

C. PROPOSED FUTURE SUPPLY DESIGN

Following the experimental runs of the C30, the engine fuel inlet pressure was observed to decrease during the loaded hydrogen runs. A lower inlet pressure was expected

due to a potential choked flow in the 6.35 mm fuel tubing because of hydrogen's low volumetric density shown in Figure 1. It is almost 4 times smaller than propane's volumetric density. The lower volumetric density implies the need for increased fuel tube sizing to increase overall mass fuel flow. Although the input pressure was expected to drop, the data showed a continual decrease in inlet pressure as the applied load increased. The C30 was unable to operate off 30 kW due to a low input fuel pressure. To avoid future problems with low fuel inlet pressure, a new hydrogen supply system was designed. The hydrogen system still contains essential safety features including two solenoid valves and a flame arrestor. The updated hydrogen supply system is shown in Figure 8.

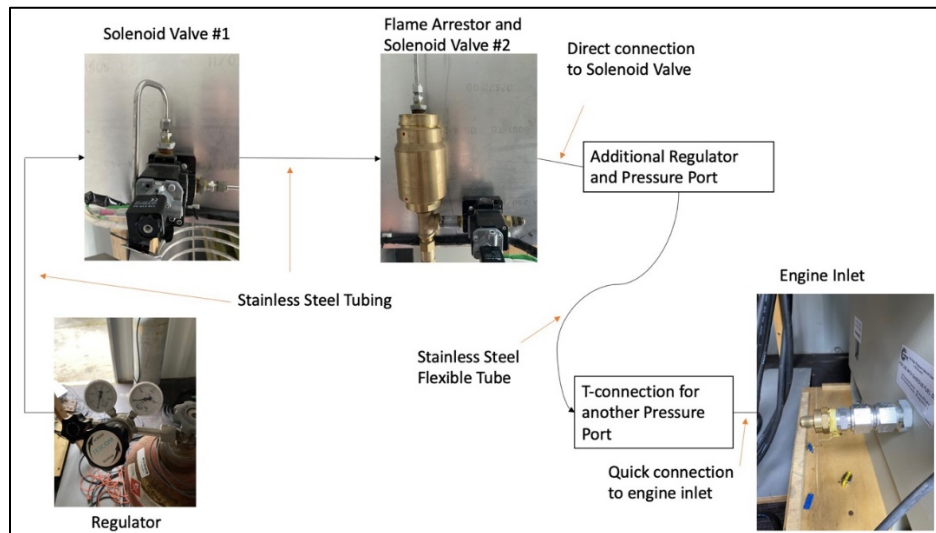


Figure 8. Updated hydrogen supply system/design

The main features added to the supply system are increased tubing sizes, from 6.35 mm to 9.52 mm, an additional flow regulator, pressure port connections, and a quick release system. The tubing sizes were increased because choked flow was assumed, due to the drastic decrease in pressure drop. The regulator was added to decrease the high back pressure after the hydrogen has traveled through the solenoid valves and flame arrestor. The pressure port connections will be used to measure the pressure throughout the system to determine where pressure drop is occurring. The quick release system was added to efficiently change between fuel sources.

THIS PAGE INTENTIONALLY LEFT BLANK

III. OPERATION OF C30 CAPSTONE

The high-pressure C30 Capstone was used for both propane and hydrogen fuel. The original fuel supply systems for the propane and hydrogen were not altered. The C30 operating procedure can be found in Appendix A. The two fuels were able to successfully run the C30. The comparisons between the two fuels are shown through tables and plots for variable loading conditions. GASTURB, a gas turbine simulation program, was also used to aid in comparing parameters for which the C30 did not have the instrumentation to measure.

A. RESULTS AND ANALYSIS

The main parameters measured by the C30 were engine speed and TET. Engine speed was selected to verify steady state operation when transitioning between applied loads. TET is measured to have an additional parameter to set up simulation data for comparisons. Table 1 shows a comparison between propane and hydrogen while under idle operation.

Table 1. C30 test results for idle operation

Fuel	Propane	Hydrogen
Input Pressure [kPa]	345	690
Fuel Valve Inlet Pressure [kPa]	343	640
Steady State TET [K]	949	952

The input pressure is the pressure specified at the exit of the fuel tank. The fuel valve inlet pressure is the pressure measured by the engine after flowing through the fuel lines. Although hydrogen has an input pressure two times larger than propane, the steady state TET's remain nearly the same. This is expected because of the removal of the three mixing tubes of the combustion chamber, and the engine control system which varies the amount of fuel to a set operating point. Hydrogen has only three points of entry while propane has six. To overcome the lack of mixing tubes, the hydrogen needs a higher input pressure.

1. Propane Fuel

Propane had an input pressure regulated to 345 kPa. This pressure was chosen because of the prior experiments conducted by Kaufmann on the high pressure C30 [6]. The C30 was able to easily transition between 5 kW – 30 kW. Figures 9 and 10 display engine speed and TET at varying loads.

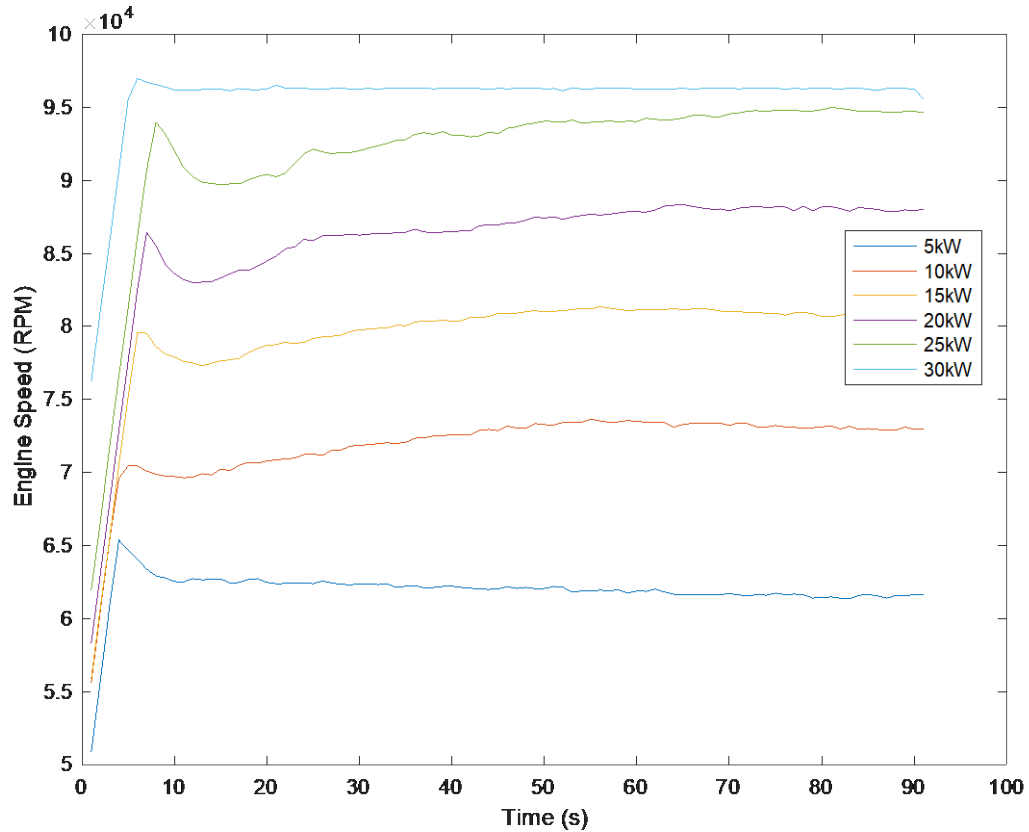


Figure 9. Engine Speed versus time for varying load propane fuel

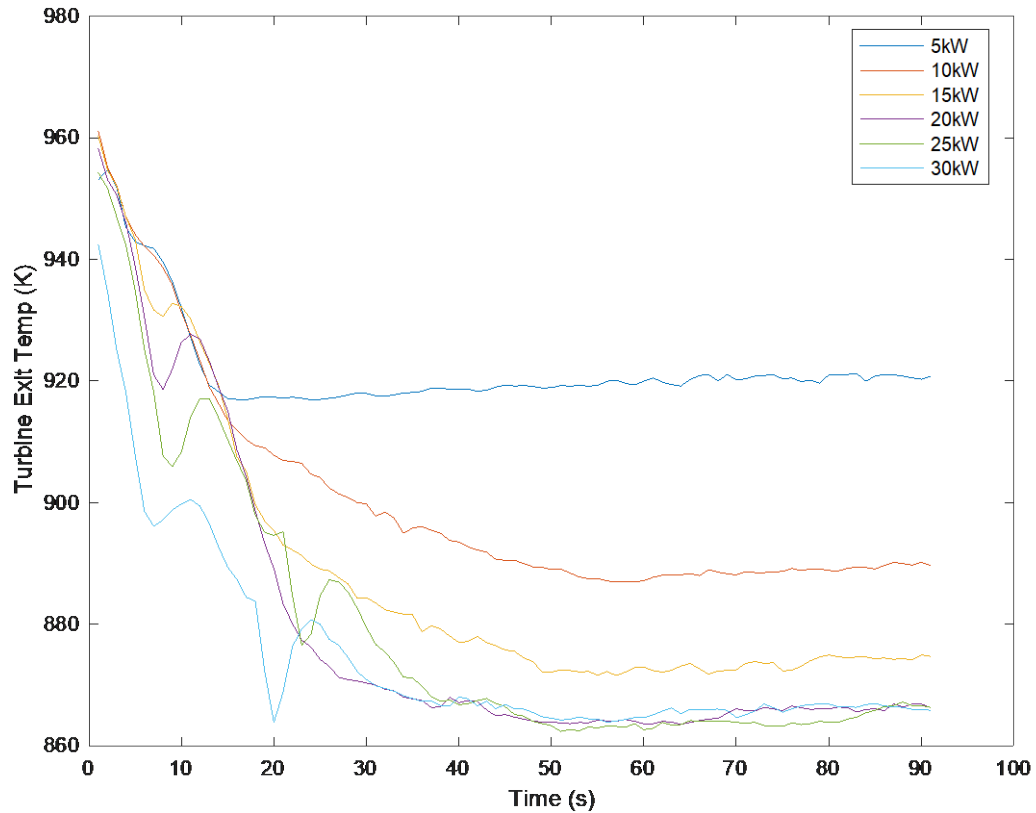


Figure 10. Turbine exit temperature versus time for varying load propane fuel

The C30 was able to reach steady state TET after 40 seconds for all of the trials. The inlet pressure remained constant through the different loads, and the steady state TET slightly decreased as the load increased. This occurred because the engine control system ensured a steady supply of fuel was inputted into the engine to obtain desired operating conditions. Table 2 shows the input pressure, inlet pressure, and steady state TET.

Table 2. C30 test results for propane variable loads

Load [kW]	5	10	15	20	25	30
Input Pressure [kPa]	345	345	345	345	345	345
Fuel Valve Inlet Pressure [kPa]	275	275	275	275	275	275
Steady State TET [K]	965	961	963	961	958	942

2. Hydrogen Fuel

Initial hydrogen testing consisted of three runs with input pressures of 276 kPa, 517 kPa, and 690 kPa with a goal of achieving idle operation. The engine ran for around 20 seconds on both the 276 kPa and 517 kPa runs. The engine entered shutoff mode soon after ignition due to low fuel inlet pressure. The engine was only reading around 35–55 kPa inlet pressure even though the system was set to give 276 kPa and 517 kPa. The last idle trial consisted of increasing the input pressure to 690 kPa. The engine successfully ignited and ran until it was intentionally shut-down because of a low fuel supply.

A six pack of hydrogen fuel was then added to the fuel supply to increase run time capability. The input pressure was set to 690 kPa and run with the load bank applied. The C30 was run at loads of 5 kW, 15 kW, 20 kW, and 25kW. Additional runs were conducted for repeatability of the experiment. The engine speed and TET are displayed against run time in Figures 11 and 12.

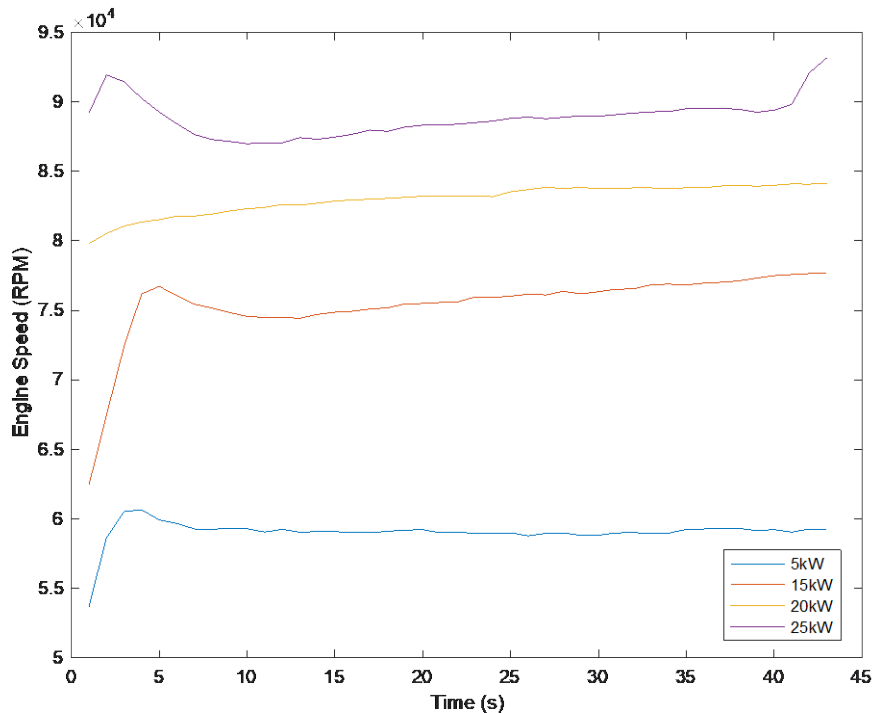


Figure 11. Engine Speed versus time for varying load hydrogen fuel

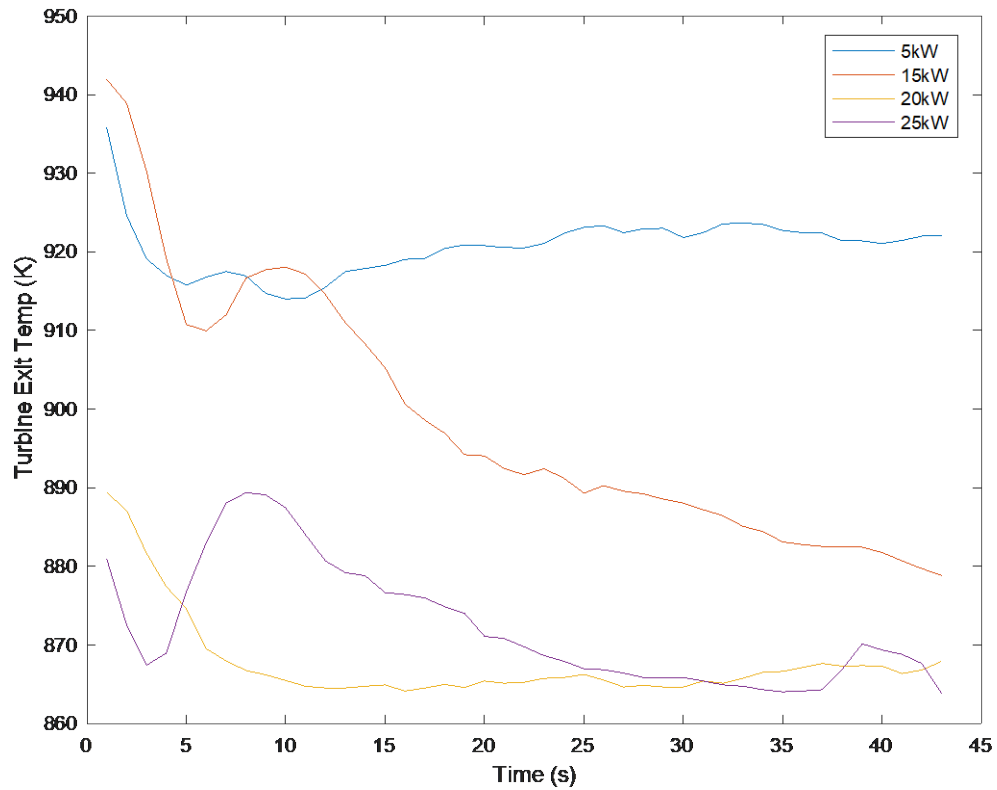


Figure 12. Turbine exit temperature versus time for varying load hydrogen fuel

The data collected was similar to expected results. The repeated runs show similar results. The 15 kW and 25 kW was not fully converged when the load was switched. The engine was easily able to transition between 5 kW – 25kW loads. Similar to the propane fuel, the TET lowered as the power demanded increased. Table 3 displays the values of input pressure, inlet pressure, steady state TET for hydrogen at different loads.

Table 3. C30 test results for hydrogen variable loads

Load [kW]	5	15	20	25
Input Pressure [kPa]	690	690	690	690
Fuel Valve Inlet Pressure [kPa]	607	552	525	469
Steady State TET [K]	936	942	932	932

Although the input pressure remained constant throughout the run, the inlet pressure decreased at each increase in load. The inlet pressure is the average pressure seen during the run. The pressure did slowly rise throughout the run which could possibly lead to the inlet pressures reaching closer to 690 kPa, but it would take an extended period of time to reach this high of a pressure. One attempt was made to run at 30 kW but was unsuccessful due to a low fuel inlet pressure. Recommendations for higher load runs are mentioned in the conclusions.

B. GASTURB COMPARISON

Although propane is not a preset fuel for a one spool turboshaft, turboprop engine simulation in GASTURB, generic fuel is an acceptable substitute because of the similar fuel heating value. Experimental data was set as parameters in GASTURB in order to accurately model the C30 engine. Adjustments were made to the simulated engine's compressor efficiency, turbine efficiency, and combustion chamber exit temperature to match the inlet pressure, TET, and shaft power of the experimental data at 30 kW.

After propane was simulated, the same engine setup was used to model a hydrogen fuel at 30 kW. The only differences, besides the fuel source, were the burner efficiency and the burner pressure ratio, which decreased by 0.1 and 0.01, respectively. GASTURB inputs and outputs can be found in Appendix B.

Off design calculations were performed to compare simulated data to experimental data at different loads. To more accurately simulate the C30 engine, different compressor maps were analyzed against the experimental data. Experimental data is plotted against GASTURB data from a standard axial compressor map and a DLR radial compressor map. The radial compressor map was chosen because the C30 operates with a radial compressor. These plots are displayed in Figures 13 and 14.

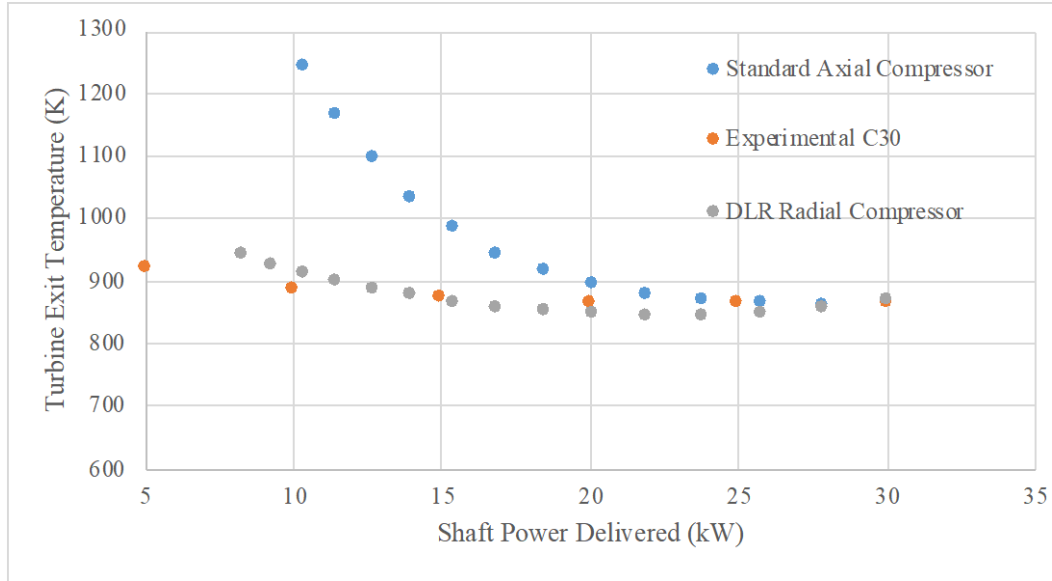


Figure 13. Comparison of GASTURB and experimental turbine exit temperature at different loads for propane fuel

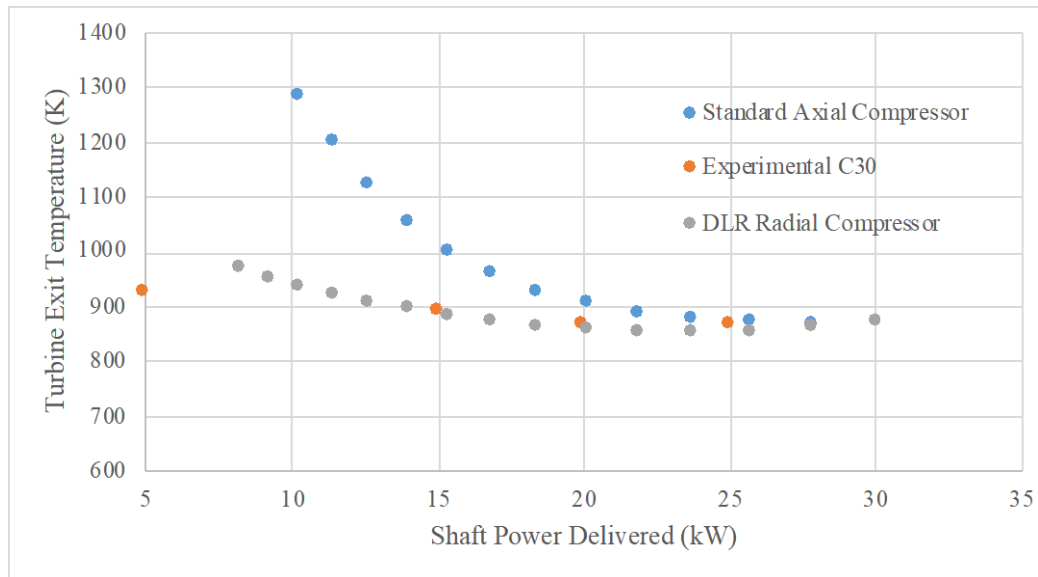


Figure 14. Comparison of GASTURB and experimental turbine exit temperature at different loads for hydrogen fuel

Altering compressor maps does not have much effect on operation between 25–30 kW. The difference is noticed when operating at conditions less than 25 kW. The standard compressor map TET has a larger error than the DLR map for the different operating loads.

Two additional parameters were compared. Those parameters were fuel mass flow rate and power specific fuel consumption. To compare the mass flow rates, the pressure readings of the hydrogen 6 pack were recorded during the runs. The recordings consisted of pressure readings before and after each load was applied. A sample of these calculations and a table of the calculated values can be found in Appendix C. The sample calculations had fuel mass flows varying from 0.0008 to 0.001 kg/s compared to the GASTURB value of approximately 0.0009 kg/s. The GASTURB values are well within the range of the experimental values. More accurate measurements can be implemented in the future to determine exact values at the different applied loads.

The final comparison analyzed was the power specific fuel consumption (PSFC). At max power of 30 kW, the hydrogen fuel has a PSFC of 0.124 kg/(kW-h). Propane fuel has a PSFC of 0.283 kg/(kW-h). Table 4 displays the PSFC comparison at different loads.

Table 4. Power specific fuel consumption for C30

Load [kW]	20	25	30
Propane [kg/(kW*h)]	0.2992	0.2879	0.2830
Hydrogen [kg/(kW*h)]	0.1397	0.1300	0.1242

Hydrogen will use less than half of the weight in fuel than propane for the same operating power and duration. These power specific fuel consumption values were taken from the data set using dlrrad compressor maps.

C. DISCUSSION AND RECOMMENDATIONS

It is hypothesized that hydrogen is an alternative, renewable fuel of the future. The experimental research of the C30 has led to valuable insight on the possibility large scale renewables for the DON. The experimental data was able to validate the simulated GASTURB data. The simulated data allowed for additional parameters to be extracted from the experimental results. Off design parameters were reliable from 15 kW and greater.

Although a new hydrogen supply system is recommended, the experimental results show that sustained hydrogen operation under load is possible. Only slight modifications need to be made to the C30. These modifications are there to increase the safety of

hydrogen fuel use by decreasing the chances of flash back. A large-scale facility would be able to operate off a single C30 with hydrogen fuel provided a steady supply of fuel was available.

The proposed hydrogen supply system should be implemented, when possible, to improve the volumetric flow rates at lower input pressures. The system design will be easy to incorporate to the existing supply lines and better improve measurements for future experimental runs. Additionally, gas valves should be placed on the pre-mix tubes for easy conversion from hydrocarbon to hydrogen fuel. The C30 is versatile enough to meet the demands of both a hydrocarbon and hydrogen fuel source.

THIS PAGE INTENTIONALLY LEFT BLANK

IV. JETCAT SIMULATIONS

The JetCat engine was designed to have initial combustion with propane fuel followed by continued operation off kerosene. Because of the two different properties of the fuels, gas and liquid, CFX modeling was implemented to gain a better understanding of a purely gaseous operation. Hydrogen fuel was the only fuel analyzed using CFX.

A. MODELING

The exact JetCat combustion chamber was not modeled. Instead, a close replica solid model of the combustion chamber was obtained [9]. The model and actual combustion chamber are shown in Figure 15.

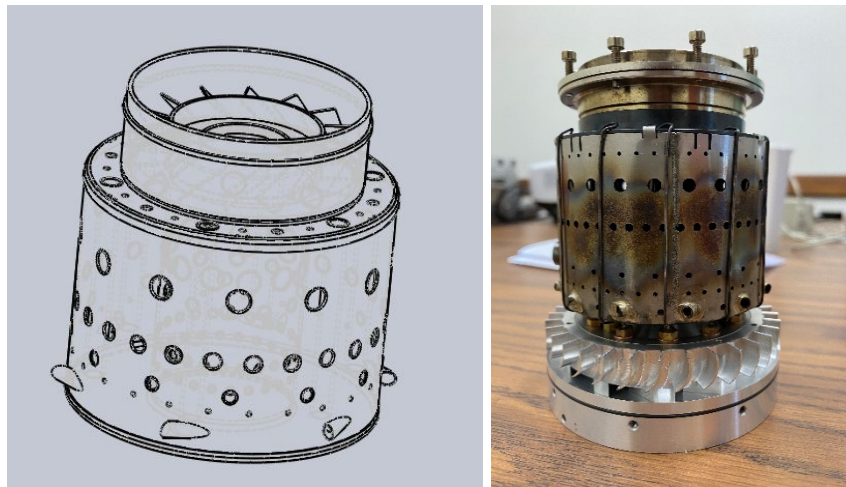


Figure 15. Combustion chamber model (left) and actual JetCat combustion chamber (right)

While the model is similar to the actual combustion chamber, there are a few differences to note. The first difference is the swirl inlets at the bottom of the chamber. The actual chamber has 12 swirl inlets, while the model only has 6. The other main difference is the fuel mixing tubes within the combustion chamber. The model has 6 tubes which run vertical within the chamber. The real JetCat has 12 tubes which run diagonal down the chamber, creating even more mixture in the reaction. These tubes were removed from the

CFX modeling. The high ignition temperatures of hydrogen could potentially melt these tubes in a real combustion process. This temperature would cause the metal to melt become FOD.

The combustion chamber cover was created in SolidWorks to create the fluid domain required for CFX. Once the cover was properly aligned to the combustion chamber, a fuel tube was inserted at the top and the combustion chamber was cut to a 60° slice to reduce the mesh size. The simulated fuel tube represents the actual fuel tube which wraps around the outside of the combustion chamber and enters through the fuel mixing tubes closest to the turbine side. The fuel mixing tubes were removed for the simulation because of hydrogens ability to combust faster than typical hydrocarbon fuels. The CFX geometry was generated by importing the geometry shown in Figure 16 and slicing the part with the combustion chamber model. The resulting geometry is shown in Figure 17.

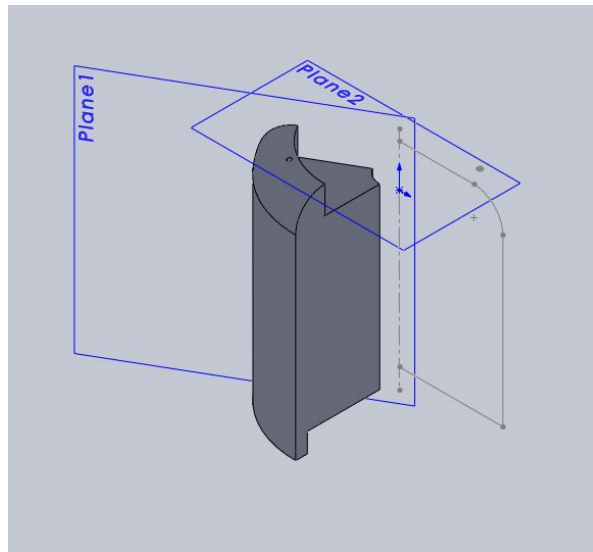


Figure 16. 60° combustion chamber cover with fuel inlet

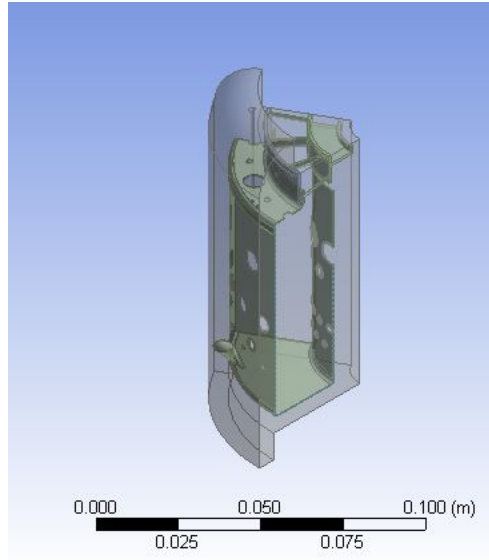


Figure 17. Sliced geometry used in CFX analysis

Once the combined geometry shown in Figure 17 was properly generated, a mesh was formed as shown in Figure 18. The mesh used the default conditions placed by CFX and did not include any additional methods or sizing factors to limit the already large computational mesh to reduce the computational load. The mesh contained 644,494 nodes and 3,417,235 elements. A new cylindrical coordinate system was generated to allow for a more accurate measuring system in CFX post.

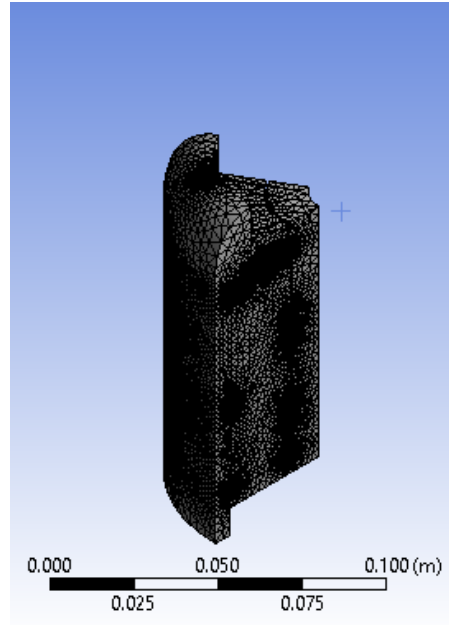


Figure 18. Mesh generated in CFX analysis

B. SETUP

The setup was modeled following the steps outlined in the ANSYS tutorial 20, ‘Combustion and Radiation in a Can Combustor,’ [10]. A GASTURB simulation for a JetCat engine operated with hydrogen fuel was also conducted to specify boundary conditions for CFX. Appendix D contains this GASTURB simulation data for propane and hydrogen fuel.

Initially, a hydrogen air mixture was selected from a pre-generated list of CFX mixtures. This was required in order to establish the fluids for the boundary conditions. Figure 19 shows the locations of the inputted boundaries.

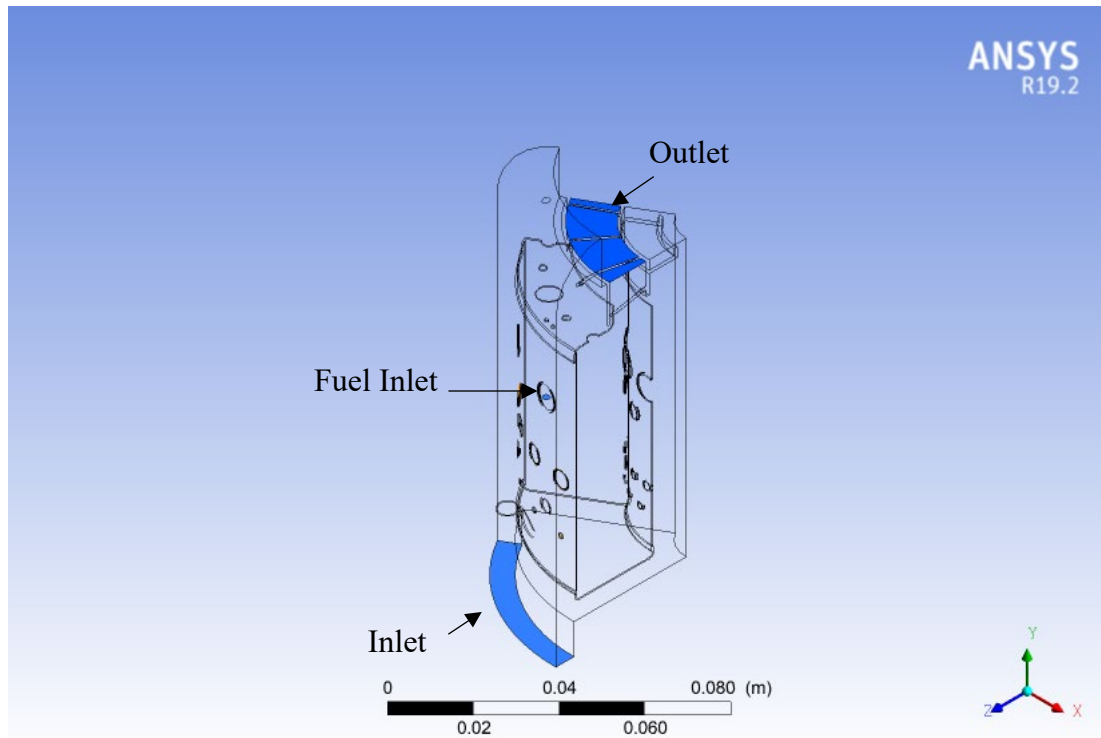


Figure 19. JetCat boundary locations

An additional domain interface with rotational periodicity was placed along the 60° cuts to simulate flow continuing throughout the combustion chamber. The specified boundary conditions can be found in Appendix E. The mass flow rates were calculated by dividing the GASTURB data of the entire engine by six to represent a 60° slice. The maximum adiabatic flame temperature of 2400 K was set to limit the maximum temperature of the simulation.

The globalization initial values are necessary to allow the simulation to have products of the reaction for the initial combustion to take place. The initial conditions for each component followed the tutorial except the component of CO_2 was removed since no carbon is used in the reaction.

The solver control was set for upwind calculations. It was not adjusted to high resolution calculations because an error would occur after 1000 iterations when running

with high resolution. The solution was steady state. The timescale control was set to auto timescale. The residual target was $1e-9$. The solution was examined every 100 iterations to inspect the results. Once the combustion was sufficient, the data was analyzed.

C. HYDROGEN-AIR COMBUSTION RESULTS AND ANALYSIS

The solution was checked for convergence using the momentum and mass residuals. The momentum and mass residuals are shown in Figure 20. Appendix F contains the additional solution residuals.

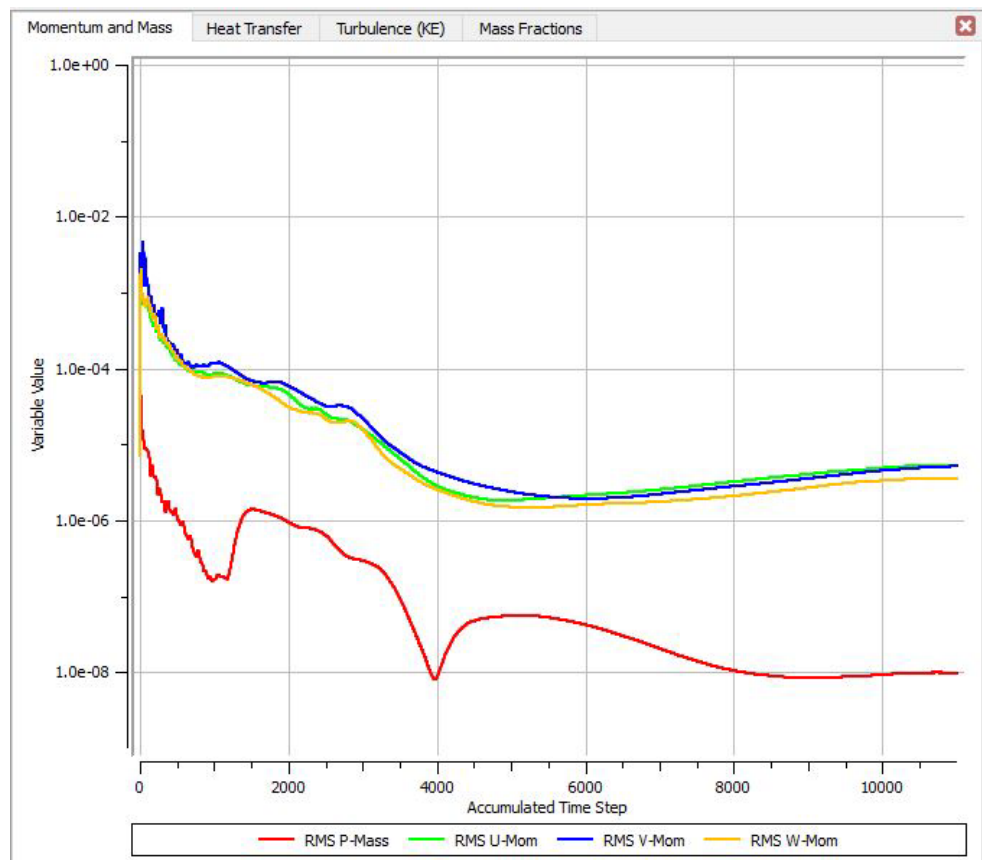


Figure 20. Momentum and mass residuals for hydrogen combustion CFX

Although it is not fully converged, the mass residuals are going slightly down and the momentum is slightly up. The flow is most likely unsteady but is being analyzed for a steady state solution. The solution stability was checked by calculating the heat addition.

The heat addition was calculated in CFX by subtracting the inlet and outlet enthalpies. The results were plotted at every 100 iterations throughout the entire solution and shown in Figure 21.

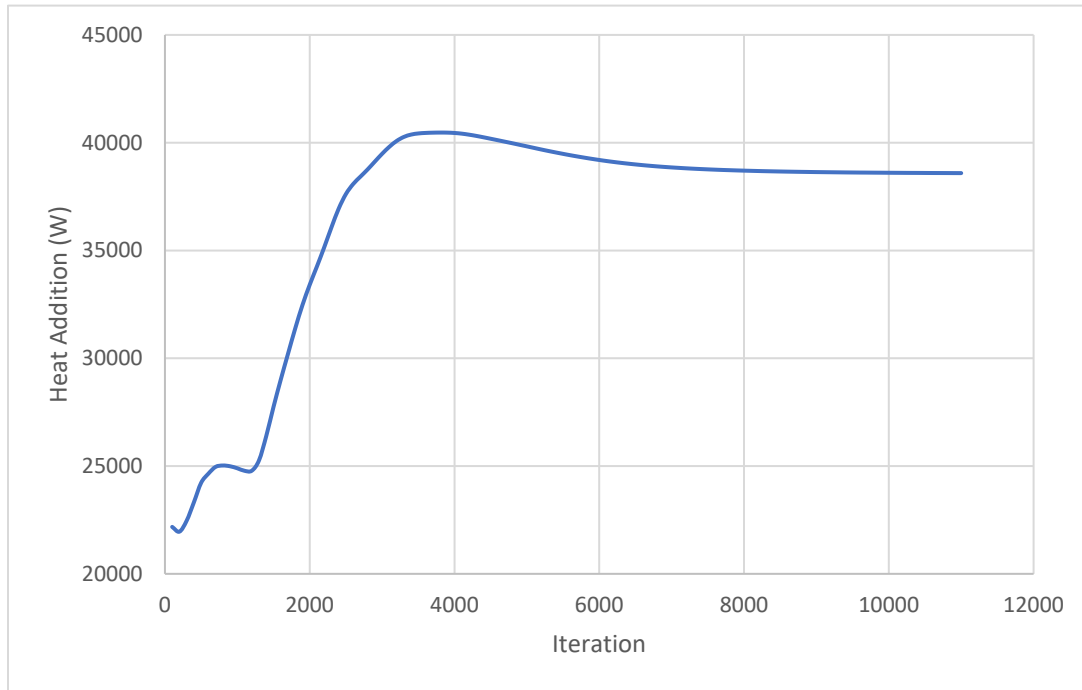


Figure 21. Heat addition throughout the combustion process

The heat addition in the combustion chamber starts off with a small increase until it drastically increases between 1200 to 3800 iterations. After it reaches a maximum heat addition of 40,470 W, the heat addition begins to level off with only a slight decrease after 8000 iterations. The simulation was run after 8000 iterations because the mass residuals were still increasing. Once the heat addition had consistently leveled off, the simulation was stopped.

Throughout the solution solver, the combustion chamber solution was observed every 100 iterations to capture the flame development. The flame development was analyzed to determine the high temperature regions of the liner and ensure the flame developed as expected for a hydrogen air mixture. Progressions of the flame development are shown in Figures 22, 23, 24, and 25.

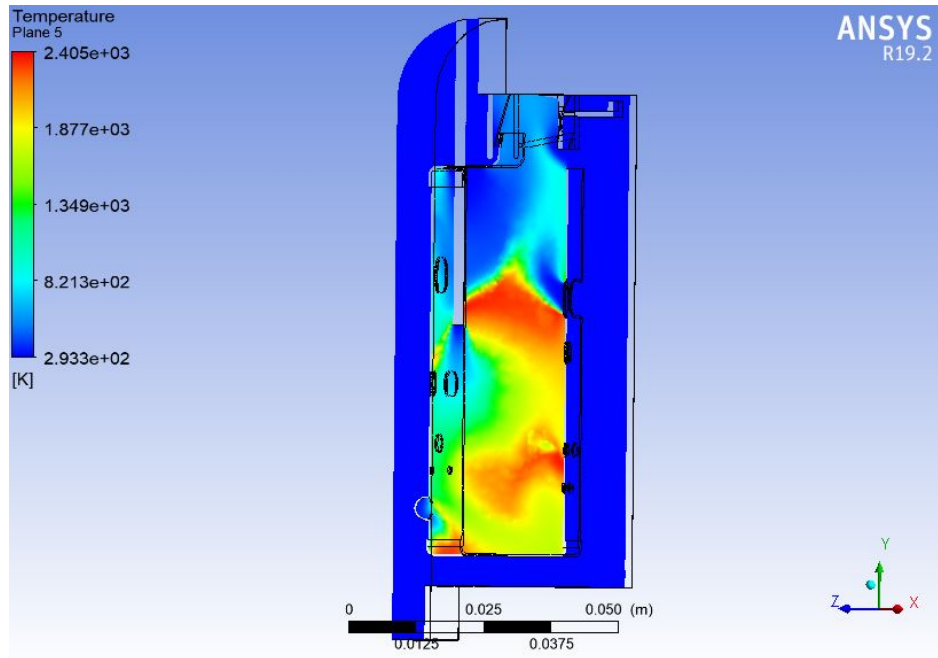


Figure 22. Hydrogen flame development at 1000 iterations

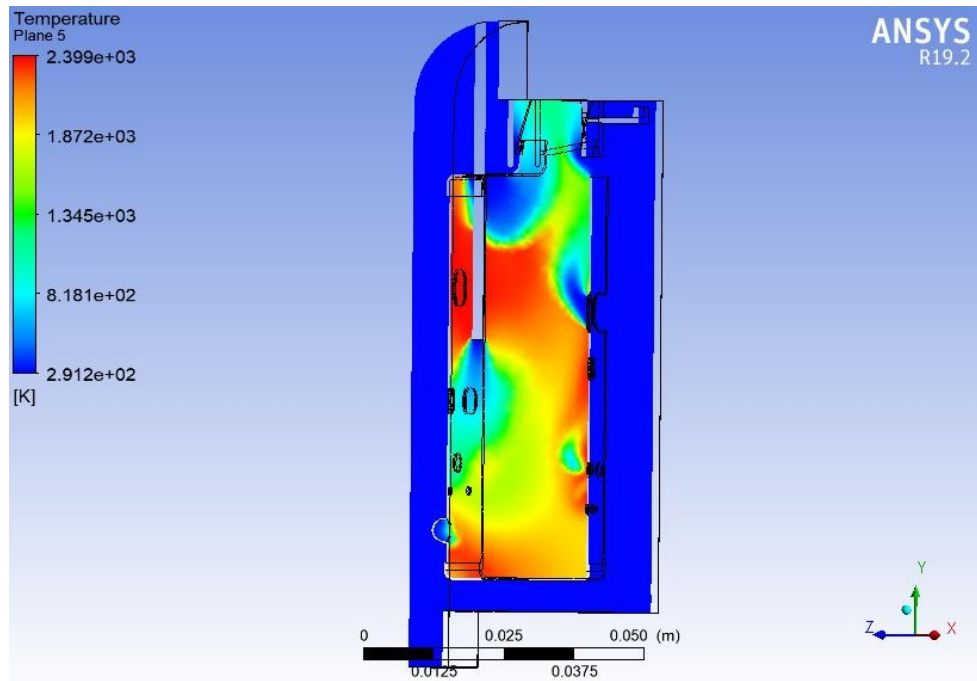


Figure 23. Hydrogen flame development at 3000 iterations

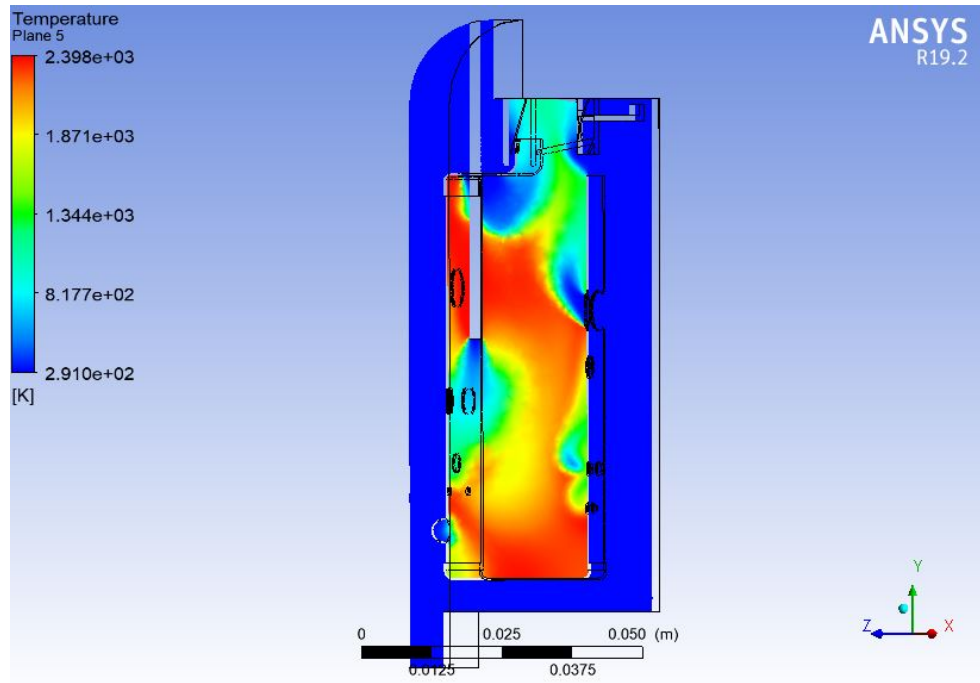


Figure 24. Hydrogen flame development at 7000 iterations

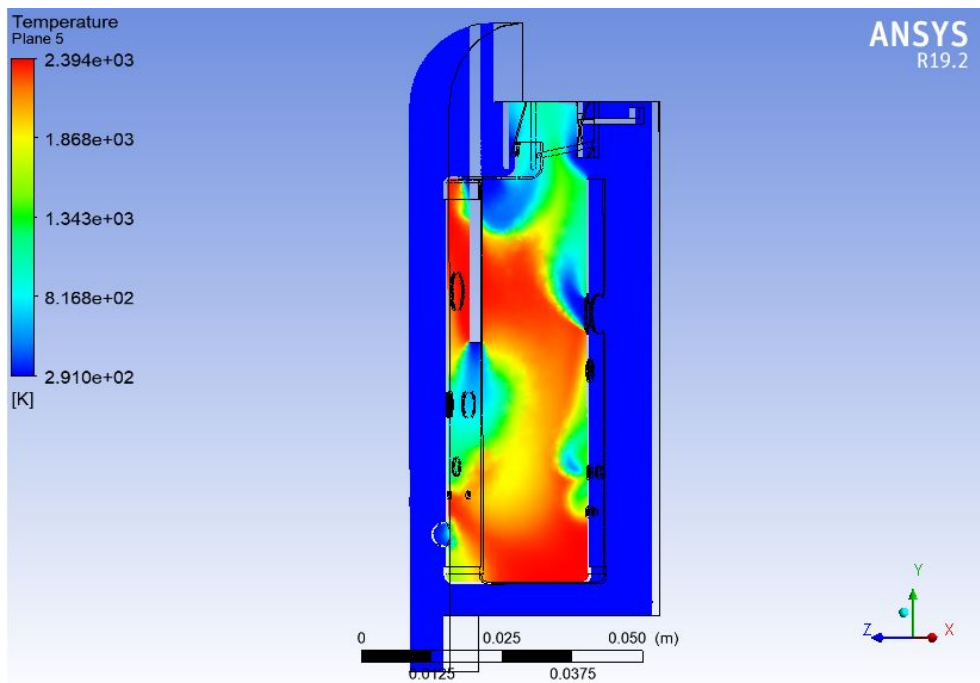


Figure 25. Hydrogen flame development at 11000 iterations

Initially, the flame is generated in the bottom of the combustion chamber. As the flame continues to develop, the hot air is pushed to the top of the chamber escapes through the outlet. The holes throughout the liner appear to be pushing cooler air through the chamber to focus the flame toward the middle of the chamber and away from the liner. Two large pockets of hot air are seen to form near the top and in the bottom inside of the combustion chamber. These two pockets contain air at 2400 K. This hot air has potential to melt through the combustion chamber liner depending on the material of the chamber. Redesign of the system may be required to lower the liner temperature.

The converged data was compared to the GASTURB data used to setup the CFX simulation. The two parameters compared were the combustion chamber exit temperature and combustion chamber pressure drop. The GASUTRB simulation calculated an exit temperature of 1080 K. The CFX simulation data was calculated by taking the area averaged temperature and pressure of the outlet. The average exit temperature was 915 K. The outlet area for 11000 iterations is shown in Figure 26.

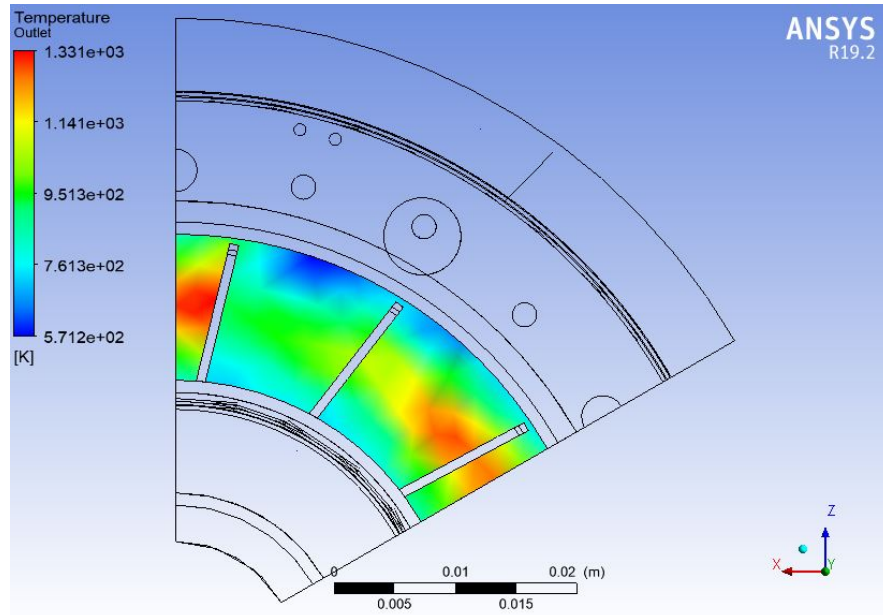


Figure 26. Combustion chamber outlet temperature at 11000 iterations

Lastly, the GASTURB simulation data between propane and hydrogen operations were compared against thrust specific fuel consumption (TSFC). The TSFC is important because it determines the weight of fuel needed for operation. The fuel comparison is shown in Table 5.

Table 5. Thrust specific fuel consumption for JetCat engine at max power

Thrust [kN]	0.06
Propane [g/(kN*s)]	42.0655
Hydrogen [g/(kN*s)]	15.1266

At identical power, hydrogen consumes almost three times less fuel by mass than propane. This difference allows hydrogen fueled gas turbine to have longer operational run times for the same mass in fuel.

D. DISCUSSION AND RECOMMENDATIONS

The JetCat combustion chamber simulations provided crucial data for future operation on hydrogen fuel. The data tells how the expected flame will form and flow, combustion chamber temperatures, and critical areas to analyze. The images of the flame shown in Figure 25 displays a high flame temperature at the top of the combustion chamber. One potential solution is to lower the fuel inlet location. Causing the tube to extend further down the combustion chamber can pull the flame closer to the center of the combustion chamber. It is important to ensure that the developed flame remains in the middle of the combustion chamber and does not exceed the melting point of the combustion chamber material. A centralized location will keep the high temperatures away from the compressor and turbine to minimize potential damages to crucial parts of the engine.

The outlet conditions help with verifying the GASTURB input data. Modification might need to be made to the GASTURB simulation to decrease combustion chamber exit temperature to match the simulation exit temperature. By manually lowering the exit temperature, compressor and turbine efficiencies will need to be adjusted to achieve the required 0.06 kN of thrust. This will also have an impact on the TSFC in Table 5.

The TSFC is an important parameter to because of its importance in increasing operational time using a hydrogen engine. This can have a major impact on DOD tactics and strategies if drones and other vehicles have longer operational times. Longer operational times can lead to fewer replenishments and refuelings.

To increase accuracy of results, a few additional changes should be made to the model. A mesh refinement study should occur to ensure the appropriately sized mesh is used. The solution solver should be adjusted from upwind to high resolutions. The CFX simulation should be setup to be a transient solver rather than a steady state solver. The fuel tube length should be varied to achieve the best heat affected zone (HAZ) for the combustion chamber. After these changes are implemented, new results can be compared to the GASTURB data prior to operational testing.

V. CONCLUSIONS AND FUTURE WORK

This thesis set out to achieve two primary goals: operate a gas turbine engine off hydrogen fuel and model a smaller JetCat engine for future experimental hydrogen runs. The C30 was able to successfully run with hydrogen fuel at different loads. The hydrogen results were compared to propane runs. Hydrogen fuel offers similar operating conditions and output power but only requires half the fuel by mass. The GASTURB simulations reinforce the experimental data and provide additional operating parameters.

The JetCat was able to be modeled and the simulation converged to a steady state solution for hydrogen fuel. The setup was aided by a GASTURB simulation which allowed for output parameters to be compared between the two simulations. Flame development images were collected to provide insight on modifications and potential hazards of hydrogen operation. TSFC was compared between propane and hydrogen fuel. It showed that hydrogen requires almost one-third the amount of fuel per mass than propane.

Hydrogen fuel has shown the ability to fulfill the desires and needs of the DOD and DON. Renewable energy can be used to generate and store hydrogen into high pressure tanks. Once fully compressed, hydrogen fuel has the ability to drastically increase operational time and decrease the need of refueling supply lines.

A. C30 CAPSTONE

The C30 Capstone should continue to be researched after a new hydrogen delivery system is installed. A larger delivery system will allow for more hydrogen to flow to the engine and allow the Capstone to operate at maximum power. Testing should be conducted at different pressure inputs and varying power loads. Future research could include a system design to incorporate hydrogen capture and compression with operation

B. JETCAT

The next stage of research for the JetCat should be to increase accuracy of the model. The flow should be simulated using a transient flow model with the following

changes addressed: mesh refinement, solver solutions, and fuel tube length. The combustion chamber material should be checked for its ability to withstand the higher hydrogen flame temperature. Operational testing could then be conducted on the JetCat.

APPENDIX A. PROCEDURE FOR OPERATION WITH HYDROGEN

The procedure to run the C30 with hydrogen was created by Kaufmann [6]. The additional bold steps are included when running with the load bank and were generated as a part of this thesis.

1. Verify that there are no leaks and that no power is supplied to the solenoid valves.
2. **Connect the load bank's ground cam-lock to an earth ground [8].**
3. **Ensure all panel switches are in the off position [8].**
4. **Keep load bank clear so air will flow freely [8].**
5. **Connect power plug to the unit [8].**
6. **Connect cam-locks to the unit [8].**
7. **Turn the Main Power switch to the ON position and the Master Load switch OFF [8].**
8. Move the battery isolation switch to the ON position, accessible via the panel labeled "BATTERY CIRCUIT BREAKER ACCESS SWITCH" [11].
9. Press the "BATT START" button (accessible via the control panel, labeled with the Capstone logo) to wake the C30 from sleep mode [11].
10. Verify that the C30 is configured for Stand Alone Operation. If not already in Stand Alone Operation Mode, configure the C30 as described in Chapter 3 of reference [11] and in reference [12].
11. Start the CRMS software, previously installed on a laptop with a RS-232 serial port [13].
12. Connect the computer to the C30 and establish communications. Open the Communications Bay to access the User Connection Board and the User Port (J6) in accordance with section 2.1, User Interface [11]. Connect the computer' RS-232 serial port to the C30 RS-232 serial port using a null modem cable. Attempts to extend the cable by connecting it in series with another modem cable are not recommended.

13. Select the “Display” tab from the options bar in the “Unit_1” window. Select “Strip Chart.”
14. Once the chart labelled “Microturbine Chart, Unit_1” appears, select the desired parameters from the drop-down menus. No more than four parameters are recommended to avoid visual clutter unless specifically required for real-time observation. All parameters will have data collected and may be charted/graphed later. The recommended parameters are “Turbine Exit Temperature,” “Battery SOC,” “Compressor Inlet Temperature,” and “Engine Speed” for a no-load run. Adjust the number of points to cover the expected runtime of the turbine. Beneath each parameter, select the upper and lower bounds. The y-axis ranges from 0 to 1, with each parameter being charted as a decimal percentage of its upper bound [13]. Recommend zero to above maximum value achieved. Avoid setting expected values such that multiple parameters chart at similar values (i.e., 0.8 for both TET and Bat SOC).
15. Select “Control Mode” from the mode drop-down menu. If prompted for a password, enter the default user port user password <USR123P> or the selected user port user password [13].
16. Select the save “File Manager” button in the top ribbon. The toggle button “Recording” should be set to manual within the “Data Recording” pane. Click the radio button “Start Recording” within the same pane; when it appears green and says “ON,” close the window. The file location may also be changed to user preference.
17. Manually open the H₂ tank valve and the manual shutoff valve.
18. Adjust the regulator to the desired fuel supply pressure.
19. Evacuate the area. (One of the test cells at the TPL was used to provide a safe barrier between the C30 and the user in the event of uncontrolled combustion.)
20. Open solenoid valve 1 remotely.
21. Open solenoid valve 2 remotely and vent for 2–4 seconds to flush the supply system with H₂ and reduce the chance of flashback.
22. Close solenoid valve 2 remotely.

23. Click “START” under “Turbine Start” and allow the C30 to start up and run [13].
- 24. Place the desired test step switch in the ON [8].**
- 25. Place the Master Load switch in the ON to engage the resistors [8].**
26. Observe data collection/conduct experiment.
27. Click “STOP” under “Turbine Start” and allow the C30 to run its shutdown procedure.
In the event of an automatic shutdown and an error message, allow the C30 to safely stop on its own [13].
28. Verify that the C30 has stopped.
- 29. Place all switches in the OFF position. Place Master Load in the OFF position [8].**
- 30. Allow fans to operate at least three minutes or until exhaust air is cool before shutting them off [8].**
- 31. Turn Main Power Switch to the OFF position and remove control power [8].**
32. Close solenoid valve 1 remotely.
33. Vent the remaining H₂ in the supply line by actuating solenoid valve 2 remotely.
34. Close the manual shutoff valve and the H₂ tank valve.
35. Turn off the control panel by moving the battery isolation switch into the OFF position, accessible via the panel labeled “BATTERY CIRCUIT BREAKER ACCESS SWITCH” [11].
36. Save the collected data and disconnect the computer from the C30.

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX B. C30 GASTURB INPUTS AND OUTPUTS

A. PROPANE INPUTS

Heat Exchanger		Exhaust Loss		Application		Steam Cooling		Water/Steam		
Basic Data		Air System		Comp Efficiency		Comp Design		Turb Efficiency		
Tip Clear.										
<div> <div>Flight</div> <div>Testbed</div> <div>Power Generation</div> </div>										
Total Temperature T1						K	296.5			
Total Pressure P1						kPa	101.325			
Ambient Pressure Pamb						kPa	101.325			
Relative Humidity [%]							0			
Inlet Corr. Flow W2Rstd						kg/s	0.31			
Intake Pressure Ratio							0.99			
Pressure Ratio							3.6			
Burner Exit Temperature						K	1100			
Burner Design Efficiency							0.9999			
Burner Partload Constant							1.6			
Fuel Heating Value						MJ/kg	46.4			
Overboard Bleed						kg/s	0			
Mechanical Efficiency							0.9999			
Burner Pressure Ratio							0.97			
Turbine Exit Duct Press Ratio							0.98			
Design Exhaust Pressure Ratio							1.03			

Fuel: Generic

Figure 27. C30 basic data inputs (generic/propane)

Basic Data		Air System		Comp Efficiency		Comp Design		Turb Efficiency		
Tip Clear.										
<div> <div>Heat Exchanger</div> <div>Exhaust Loss</div> <div>Application</div> <div>Steam Cooling</div> <div>Water/Steam</div> </div>										
The Options: <div> <input type="radio"/> 1: w/o Heat Exchanger </div> <div> <input checked="" type="radio"/> 2: with Heat Exchanger (Method 1) </div> <div> <input type="radio"/> 3: with Heat Exchanger (Method 2) </div>										
Heat Exchanger Effectiveness							0.8			
Heat Exchanger Design P35/P3							0.99			
Heat Exchanger Design P7/P6							0.9			

Fuel: Generic

Figure 28. C30 heat exchanger data inputs (generic/propane)

Heat Exchanger		Exhaust Loss		Application		Steam Cooling		Water/Steam	
Basic Data		Air System		Comp Efficiency		Comp Design		Turb Efficiency	
								Tip Clear.	
Rel. Handling Bleed								0	
Rel. Enthalpy of Handling Bleed								1	
Rel. Overboard Bleed W Bld/W2								0.01	
Rel. Enthalpy of Overb. Bleed								1	
Recirculating Bleed W reci/W2								Off Design Input Only	
Rel. Enthalpy of Recirc Bleed								1	
NGV Cooling Air W CI NGV/W2								0.01	
Rotor Cooling Air W CI/W2								0	
Cooling Air Pumping Diameter						m		0	

Fuel:
 Generic

Figure 29. C30 air system data inputs (generic/propane)

Heat Exchanger		Exhaust Loss		Application		Steam Cooling		Water/Steam	
Basic Data		Air System		Comp Efficiency		Comp Design		Turb Efficiency	
								Tip Clear.	
The Options: <input checked="" type="radio"/> 1: isentropic <input type="radio"/> 2: polytropic <input type="radio"/> 3: calculate it									
Isentr.Compr.Efficiency								0.8	

Fuel:
 Generic

Figure 30. C30 compressor efficiency data inputs (generic/propane)

Heat Exchanger		Exhaust Loss		Application		Steam Cooling		Water/Steam		Fuel:	
Basic Data		Air System		Comp Efficiency		Comp Design		Turb Efficiency		Tip Clear.	
The Options:											
<input type="radio"/> 1: no <input checked="" type="radio"/> 2: yes											
Compressor Tip Speed						m/s		350			
Compressor Inlet Radius Ratio								0.5			
Compressor Inlet Mach Number								0.54			
Engine Inl/Compr Tip Diam Ratio								1			
min Compr Inlet Hub Diameter						m		0			

Figure 31. C30 compressor design data inputs (generic/propane)

Heat Exchanger		Exhaust Loss		Application		Steam Cooling		Water/Steam		Fuel:	
Basic Data		Air System		Comp Efficiency		Comp Design		Turb Efficiency		Tip Clear.	
The Options:											
<input checked="" type="radio"/> 1: isentropic <input type="radio"/> 2: polytropic <input type="radio"/> 3: calculate it											
Isentr.Turbine Efficiency								0.89			

Figure 32. C30 turbine efficiency data inputs (generic/propane)

B. PROPANE OUTPUTS

Summary Compressor Air System									
Station	W kg/s	T K	P kPa	WRstd kg/s					
amb		296.50	101.325		PWSD	=	30.1	kW	
1	0.303	296.50	101.325		PSFC	=	0.3048	kg/(kW*h)	
2	0.303	296.50	100.312	0.310	Heat Rate=		13143.5	kJ/(kW*h)	
3	0.303	458.91	361.122	0.107	Therm Eff=		0.2739		
31	0.300	458.91	361.122		WF	=	0.00255	kg/s	
35	0.296	786.65	357.511		P35/P3	=	0.99000		
4	0.299	1100.00	346.786	0.171	P7/P6	=	0.90000		
41	0.302	1096.96	346.786	0.172	s NOx	=	0.39390		
49	0.302	867.20	118.327		incidence=		0.00000	°	
5	0.302	867.20	118.327	0.449	XM8	=	0.2077		
6	0.302	867.20	115.961		A8	=	0.0049	m²	
7	0.302	551.97	104.365						
8	0.302	551.97	104.365	0.406	P8/Ps8	=	1.03000		
Bleed	0.003	458.91	361.122		WBld/W2	=	0.01000		

Efficiencies:	isent	polytr	RNI	P/P	P2/P1	=	0.99000		
Compressor	0.8000	0.8318	0.957	3.600	W_NGV/W2	=	0.01000		
Burner	0.9999			0.970	WCL/W2	=	0.00000		
Turbine	0.8900	0.8757	0.712	2.931	Loading	=	100.00	%	
Heat Exch.	0.8000				e45 th	=	0.88988		
Generator	1.0000				PW_gen	=	30.1	kW	

Spool mech Eff	0.9999	Nom Spd	126984	rpm	P6/P5	=	0.9800		

hum [%]	war0	FHV	Fuel						
0.0	0.00000	43.124	Generic						

Figure 33. C30 summary of outputs (generic/propane)

Summary			Compressor	Air System
Input:				
Compressor Tip Speed	m/s	350.00000		
Compressor Inlet Radius Ratio		0.50000		
Compressor Inlet Mach Number		0.54000		
Engine Inl/Compr Tip Diam Ratio		1.00000		
min Compr Inlet Hub Diameter	m	0.00000		
Output:				
Compressor Tip circumf. Mach No		1.04307		
Compressor Tip relative Mach No		1.17456		
Design Spool Speed	[RPM]	126983.94		
Compr Inlet Tip Diameter	m	0.05264		
Compr Inlet Hub Diameter	m	0.02632		
Calculated Compr Radius Ratio		0.50000		
Aerodynamic Interface Plane	m ²	0.00218		
Corr.Flow/Area Compr	kg/(s*m ²)	189.91932		

Figure 34. C30 compressor data outputs (generic/propane)

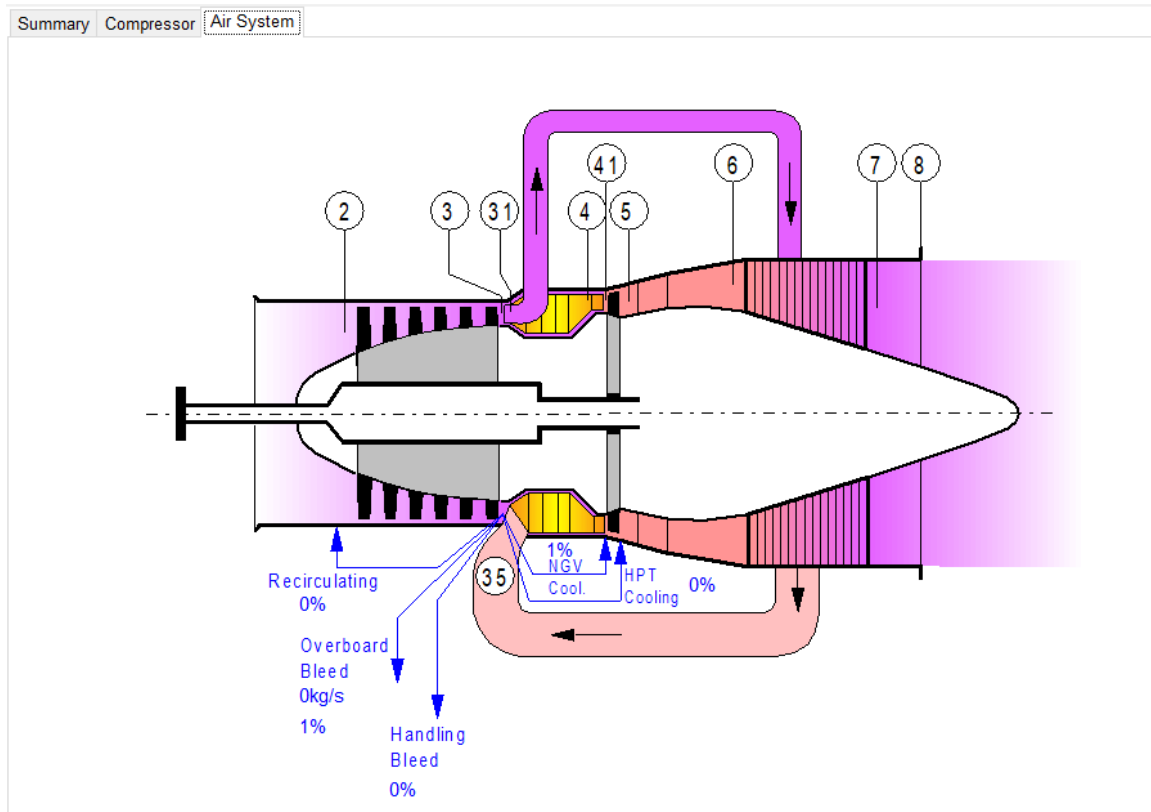


Figure 35. C30 air system outputs (generic/propane)

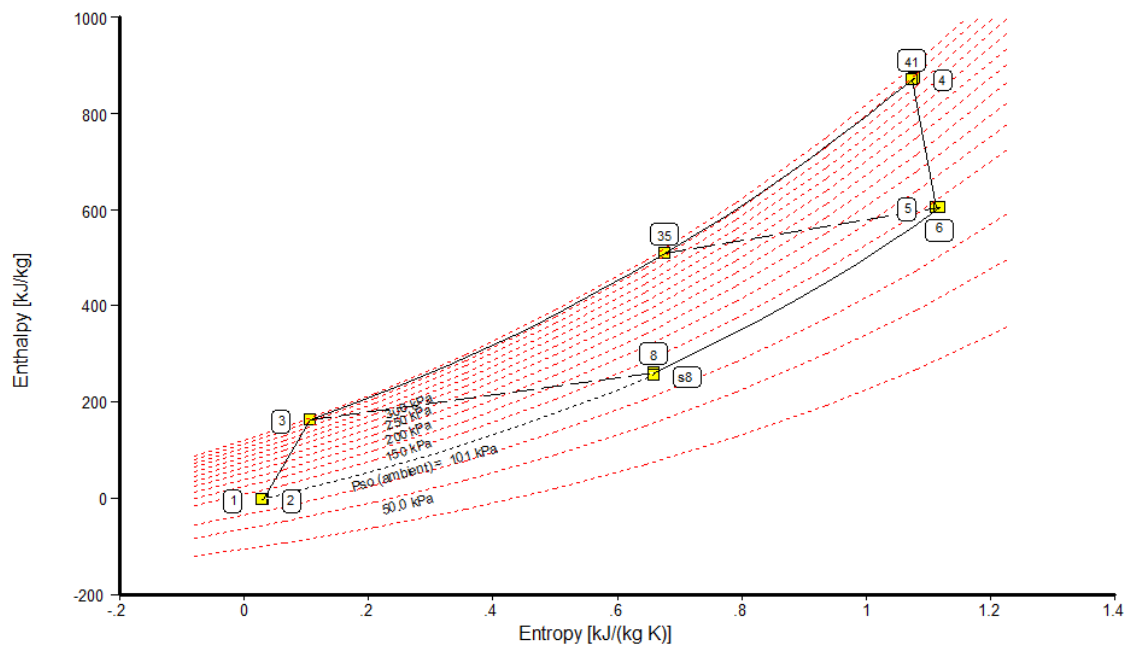


Figure 36. C30 enthalpy-entropy diagram (generic/propane)

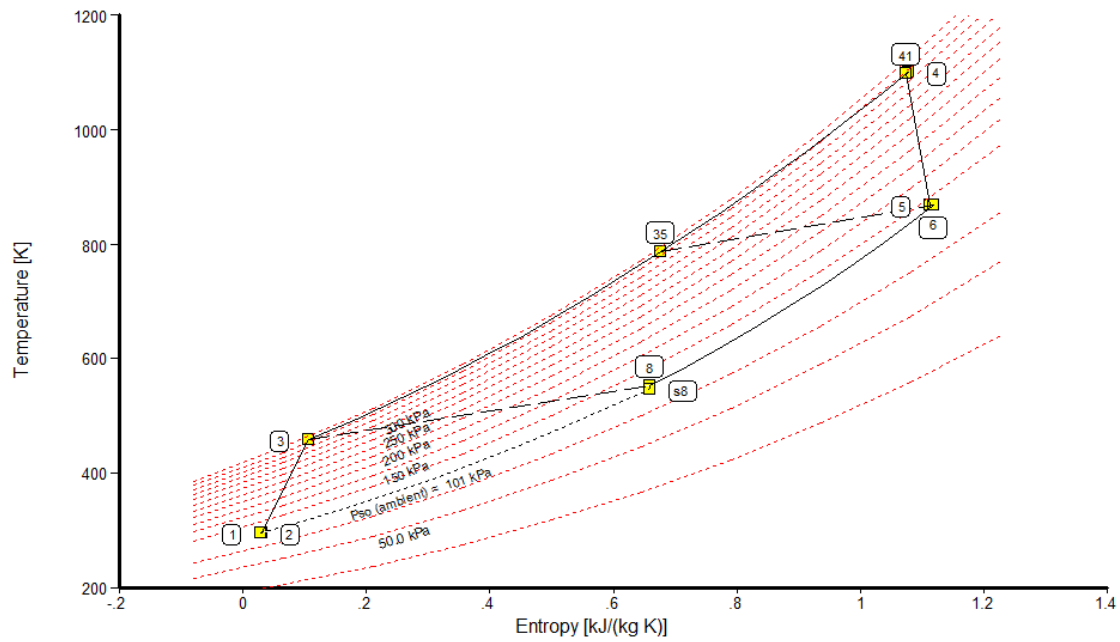


Figure 37. C30 temperature-entropy diagram(generic/propane)

C. HYDROGEN INPUTS

Heat Exchanger		Exhaust Loss		Application		Steam Cooling		Water/Steam		Fuel:	
Basic Data		Air System		Comp Efficiency		Comp Design		Turb Efficiency		Tip Clear.	
<div> <div>Flight</div> <div>Testbed</div> <div>Power Generation</div> </div>											
Total Temperature T1				K		296.5					
Total Pressure P1				kPa		101.325					
Ambient Pressure Pamb				kPa		101.325					
Relative Humidity [%]						0					
Inlet Corr. Flow W2Rstd				kg/s		0.31					
Intake Pressure Ratio						0.99					
Pressure Ratio						3.6					
Burner Exit Temperature				K		1100					
Burner Design Efficiency						0.9					
Burner Partload Constant						1.6					
Fuel Heating Value				MJ/kg		118.429					
Overboard Bleed				kg/s		0					
Mechanical Efficiency						0.9999					
Burner Pressure Ratio						0.95					
Turbine Exit Duct Press Ratio						0.98					
Design Exhaust Pressure Ratio						1.03					

Figure 38. C30 basic data inputs (hydrogen)

Basic Data	Air System	Comp Efficiency	Comp Design	Turb Efficiency	Tip Clear.
Heat Exchanger	Exhaust Loss	Application	Steam Cooling	Water/Steam	
The Options:					
<input type="radio"/> 1: w/o Heat Exchanger <input checked="" type="radio"/> 2: with Heat Exchanger (Method 1) <input type="radio"/> 3: with Heat Exchanger (Method 2)					
Heat Exchanger Effectiveness					0.8
Heat Exchanger Design P35/P3					0.99
Heat Exchanger Design P7/P6					0.9

Fuel: Hydrogen

Figure 39. C30 heat exchanger inputs (hydrogen)

Heat Exchanger	Exhaust Loss	Application	Steam Cooling	Water/Steam
Basic Data	Air System	Comp Efficiency	Comp Design	Turb Efficiency
Tip Clear.				

Rel. Handling Bleed		0
Rel. Enthalpy of Handling Bleed		1
Rel. Overboard Bleed W Bld/W2		0.01
Rel. Enthalpy of Overb. Bleed		1
Recirculating Bleed W reci/W2		Off Design Input Only
Rel. Enthalpy of Recirc Bleed		1
NGV Cooling Air W CI/NGV/W2		0.01
Rotor Cooling Air W CI/W2		0
Cooling Air Pumping Diameter	m	0

Fuel: Hydrogen

Figure 40. C30 air system inputs (hydrogen)

Heat Exchanger		Exhaust Loss		Application		Steam Cooling		Water/Steam		Fuel:
Basic Data		Air System		Comp Efficiency		Comp Design		Turb Efficiency		Tip Clear.
The Options:										
<input checked="" type="radio"/> 1: isentropic <input type="radio"/> 2: polytropic <input type="radio"/> 3: calculate it										
Isentr.Compr.Efficiency								0.8		

Figure 41. C30 compressor efficiency inputs (hydrogen)

Heat Exchanger		Exhaust Loss		Application		Steam Cooling		Water/Steam		Fuel:
Basic Data		Air System		Comp Efficiency		Comp Design		Turb Efficiency		Tip Clear.
The Options:										
<input type="radio"/> 1: no <input checked="" type="radio"/> 2: yes										
Compressor Tip Speed						m/s		350		
Compressor Inlet Radius Ratio								0.5		
Compressor Inlet Mach Number								0.54		
Engine Inl/Compr Tip Diam Ratio								1		
min Compr Inlet Hub Diameter						m		0		

Figure 42. C30 compressor design inputs (hydrogen)

Heat Exchanger		Exhaust Loss		Application		Steam Cooling		Water/Steam		Fuel:
Basic Data		Air System		Comp Efficiency		Comp Design		Turb Efficiency		Tip Clear.
The Options:										
<input checked="" type="radio"/> 1: isentropic <input type="radio"/> 2: polytropic <input type="radio"/> 3: calculate it										
Isentr.Turbine Efficiency								0.89		

Figure 43. C30 turbine efficiency inputs (hydrogen)

D. HYDROGEN OUTPUTS

Summary Compressor Air System									
Station	W kg/s	T K	P kPa	WRstd kg/s					
amb		296.50	101.325		PWSD	=	30.1	kW	
1	0.303	296.50	101.325		PSFC	=	0.1242	kg/(kW*h)	
2	0.303	296.50	100.312	0.310	Heat Rate	=	14709.7	kJ/(kW*h)	
3	0.303	458.90	361.122	0.107	Therm Eff	=	0.2447		
31	0.300	458.90	361.122		WF	=	0.00104	kg/s	
35	0.296	789.40	357.511		P35/P3	=	0.99000		
4	0.298	1100.00	339.636	0.175	P7/P6	=	0.90000		
41	0.301	1097.03	339.636	0.177	s NOx	=	0.39951		
49	0.301	870.50	118.327		incidence	=	0.00000	°	
5	0.301	870.50	118.327	0.452	XM8	=	0.2079		
6	0.301	870.50	115.961		A8	=	0.0049	m²	
7	0.301	556.80	104.365						
8	0.301	556.80	104.365	0.409	P8/Ps8	=	1.03000		
Bleed	0.003	458.90	361.122		WBld/W2	=	0.01000		
-----					P2/P1	=	0.99000		
Efficiencies:	isent	polytr	RNI	P/P	W_NGV/W2	=	0.01000		
Compressor	0.8000	0.8318	0.957	3.600	WCL/W2	=	0.00000		
Burner	0.9000			0.950	Loading	=	100.00	%	
Turbine	0.8900	0.8760	0.697	2.870	e45 th	=	0.88976		
Heat Exch.	0.8000								
Generator	1.0000				PW_gen	=	30.1	kW	
-----					P6/P5	=	0.9800		
Spool mech Eff	0.9999	Nom Spd	126984	rpm					

hum [%]	war0	FHV	Fuel						
0.0	0.00000	118.429	Hydrogen						

Figure 44. C30 summary of outputs (hydrogen)

Summary	Compressor	Air System
Input:		
Compressor Tip Speed	m/s	350.00000
Compressor Inlet Radius Ratio		0.50000
Compressor Inlet Mach Number		0.54000
Engine Inl/Compr Tip Diam Ratio		1.00000
min Compr Inlet Hub Diameter	m	0.00000
Output:		
Compressor Tip circumf. Mach No		1.04307
Compressor Tip relative Mach No		1.17456
Design Spool Speed	[RPM]	126983.83
Compr Inlet Tip Diameter	m	0.05264
Compr Inlet Hub Diameter	m	0.02632
Calculated Compr Radius Ratio		0.50000
Aerodynamic Interface Plane	m ²	0.00218
Corr.Flow/Area Compr	kg/(s*m ²)	189.91898

Figure 45. C30 compressor data outputs (hydrogen)

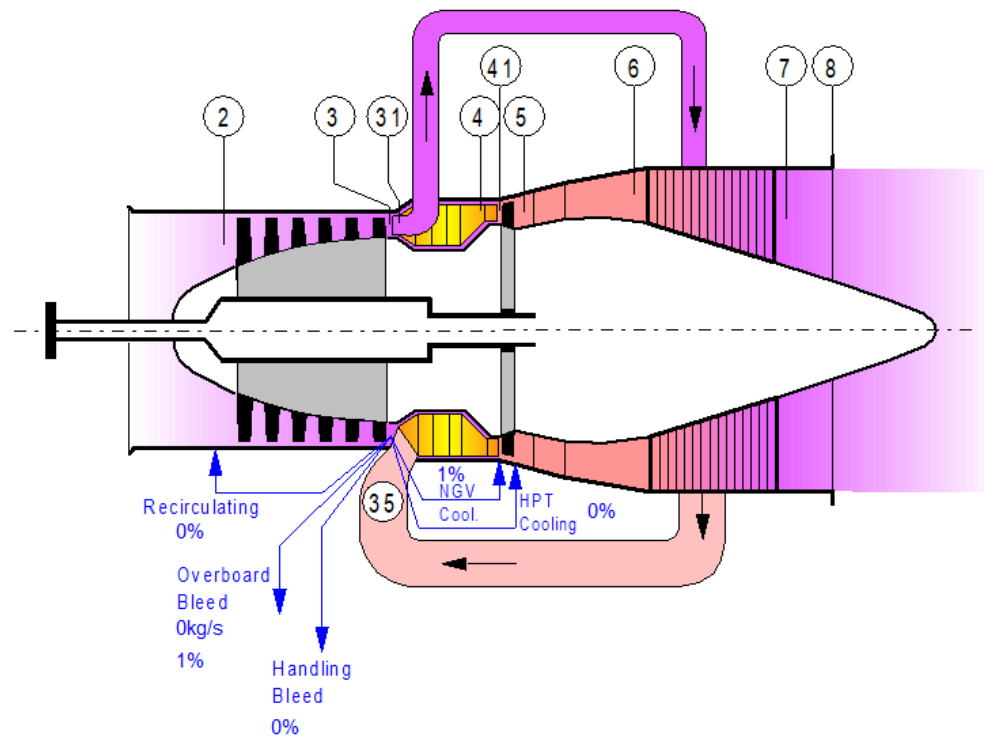


Figure 46. C30 air system outputs (hydrogen)

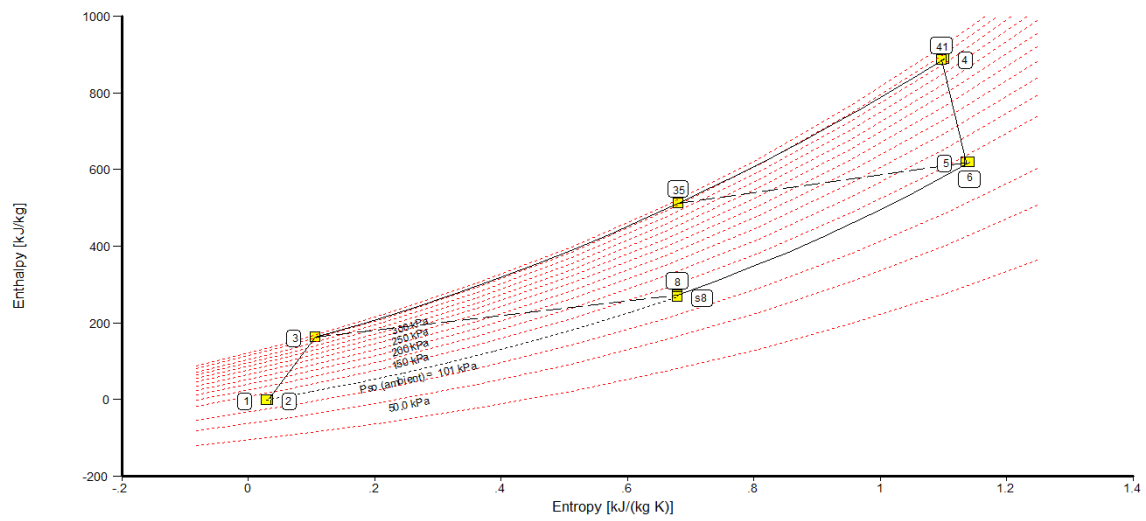


Figure 47. C30 enthalpy-entropy diagram (hydrogen)

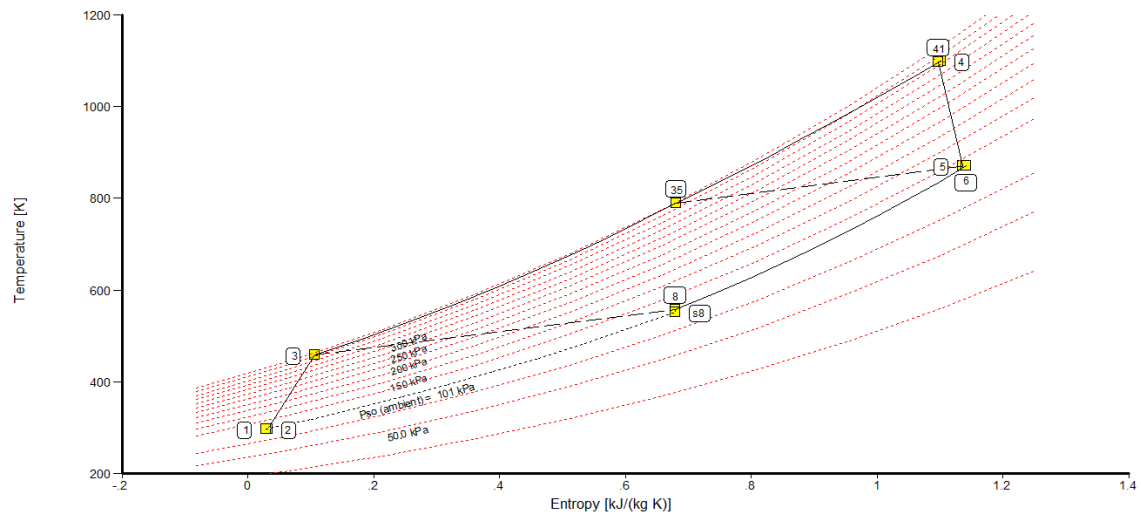


Figure 48. C30 temperature-entropy diagram (hydrogen)

APPENDIX C. C30 HYDROGEN FUEL MASS FLOW CALCULATIONS

Using the hydrogen 6 pack pressure readings and the ideal gas law, the mass flow of hydrogen fuel was able to be calculated. Because of the phase change occurring in propane fuel, only hydrogen mass flow was calculated. The temperature was assumed to be at standard conditions.

$$pV = mRT$$

$$m = \frac{pV}{RT}$$

$$\dot{m} = \frac{m}{s}, \text{ s is run time in seconds}$$

Load (kW)	Starting Pressure (kPa)	Ending Pressure (kPa)	Run time (s)
15	11721	11376	90
20	11376	10895	90

Load (kW)	Mass Beginning (kg)	Mass End (kg)	Mass difference (kg)	Mass Flow (kg/s)
15	2.4590	2.3866	0.0724	8.04E-04
20	2.3866	2.2857	0.1009	1.12E-03

THIS PAGE IS INTENTIONALLY LEFT BLANK

APPENDIX D. JETCAT GASTURB INPUTS AND OUTPUTS

A. PROPANE INPUTS

Tip Clear.		Reheat		Nozzle Selection		Nozzle Calculation	
Basic Data		Air System		Comp Efficiency		Comp Design	
Turb Efficiency							
<div> <div>Flight</div> <div>Testbed</div> </div>							
Altitude		m				0	
Delta T from ISA		K				0	
Relative Humidity [%]						0	
Mach Number						0	
Inlet Corr. Flow W2Rstd		kg/s				0.16	
Intake Pressure Ratio						0.99	
Pressure Ratio						2	
Burner Exit Temperature		K				1080	
Burner Design Efficiency						0.9999	
Burner Partload Constant						1.6	
Fuel Heating Value		MJ/kg				43.124	
Overboard Bleed		kg/s				0	
Power Offtake		kW				0	
Mechanical Efficiency						0.9999	
Burner Pressure Ratio						0.97	
Turbine Exit Duct Press Ratio						0.98	

Fuel: Generic

Figure 49. JetCat basic data (generic/propane)

Basic Data		Air System		Comp Efficiency		Comp Design		Turb Efficiency	
Tip Clear.		Reheat		Nozzle Selection		Nozzle Calculation			
The Options: <div> <div> <input checked="" type="radio"/> 1: Convergent Nozzle </div> <div> <input type="radio"/> 2: Con/Di Nozzle </div> </div>									

Fuel: Generic

Figure 50. JetCat nozzle selection (generic/propane)

Tip Clear.	Reheat	Nozzle Selection		Nozzle Calculation
Basic Data	Air System	Comp Efficiency	Comp Design	Turb Efficiency
Rel. Handling Bleed				0
Rel. Enthalpy of Handling Bleed				1
Rel. Overboard Bleed W Bld/W2				0.01
Rel. Enthalpy of Overb. Bleed				1
Recirculating Bleed W reci/W2				Off Design Input Only
Rel. Enthalpy of Recirc Bleed				1
NGV Cooling Air W CI NGV/W2				0.05
Rotor Cooling Air W CI/W2				0.05
Cooling Air Pumping Diameter		m		0

Fuel:
 Generic v

Air system (generic/propane)

Basic Data	Air System	Comp Efficiency	Comp Design	Turb Efficiency
Tip Clear.	Reheat	Nozzle Selection	Nozzle Calculation	
The Options: <input checked="" type="radio"/> 1: no Reheat <input type="radio"/> 2: Standard Reheat Calc <input type="radio"/> 3: Special Reheat Calc				

Fuel:
 Generic v

Figure 51. JetCat reheat (generic/propane)

Tip Clear.		Reheat		Nozzle Selection		Nozzle Calculation		Fuel: Generic ▾
Basic Data		Air System		Comp Efficiency		Comp Design		
The Options: <input checked="" type="radio"/> 1: no <input type="radio"/> 2: yes								
Nominal Spool Speed								14000

Figure 52. JetCat compressor design (generic/propane)

Tip Clear.		Reheat		Nozzle Selection		Nozzle Calculation		Fuel: Generic ▾
Basic Data		Air System		Comp Efficiency		Comp Design		
The Options: <input checked="" type="radio"/> 1: isentropic <input type="radio"/> 2: polytropic <input type="radio"/> 3: calculate it								
Isentr.Compr.Efficiency								0.8

Figure 53. JetCat compressor efficiency (generic/propane)

Tip Clear.		Reheat		Nozzle Selection		Nozzle Calculation		Fuel: Generic ▾
Basic Data		Air System		Comp Efficiency		Comp Design		
The Options: <input checked="" type="radio"/> 1: isentropic <input type="radio"/> 2: polytropic <input type="radio"/> 3: calculate it								
Isentr.Turbine Efficiency								0.85

Figure 54. JetCat turbine efficiency (generic/propane)

B. PROPANE OUTPUTS

Summary		Air System					
Station	W kg/s	T K	P kPa	WRstd kg/s			
amb		288.15	101.325		FN	=	0.06 kN
1	0.158	288.15	101.325		TSFC	=	42.0655 g/(kN*s)
2	0.158	288.15	100.312	0.160	FN/W2	=	395.58 m/s
3	0.158	366.81	200.624	0.090	Prop Eff	=	0.0000
31	0.141	366.81	200.624		eta core	=	0.1155
4	0.144	1080.00	194.605	0.145			
41	0.152	1045.96	194.605	0.150	WF	=	0.00264 kg/s
49	0.152	975.47	138.767		s NOx	=	0.03606
5	0.159	947.62	138.767	0.211	XM8	=	0.6763
6	0.159	947.62	135.992		A8	=	0.0011 m²
8	0.159	947.62	135.992	0.215	P8/Pamb	=	1.3421
Bleed	0.002	366.81	200.624		WBld/W2	=	0.01000
-----					Ang8	=	20.00 °
P2/P1 = 0.9900	P4/P3 = 0.9700	P6/P5 = 0.9800			CD8	=	0.9167
Efficiencies:	isent	polytr	RNI	P/P	W_NGV/W2	=	0.05000
Compressor	0.8000	0.8184	0.990	2.000	WCL/W2	=	0.05000
Burner	0.9999			0.970	Loading	=	100.00 %
Turbine	0.8500	0.8446	0.422	1.402	e45 th	=	0.83485
-----					far7	=	0.01681
Spool mech Eff	0.9999	Nom Spd	14000 rpm		PWX	=	0.00 kW

hum [%]	war0	FHV	Fuel				
0.0	0.00000	43.124	Generic				

Figure 55. JetCat summary of outputs (generic/propane)

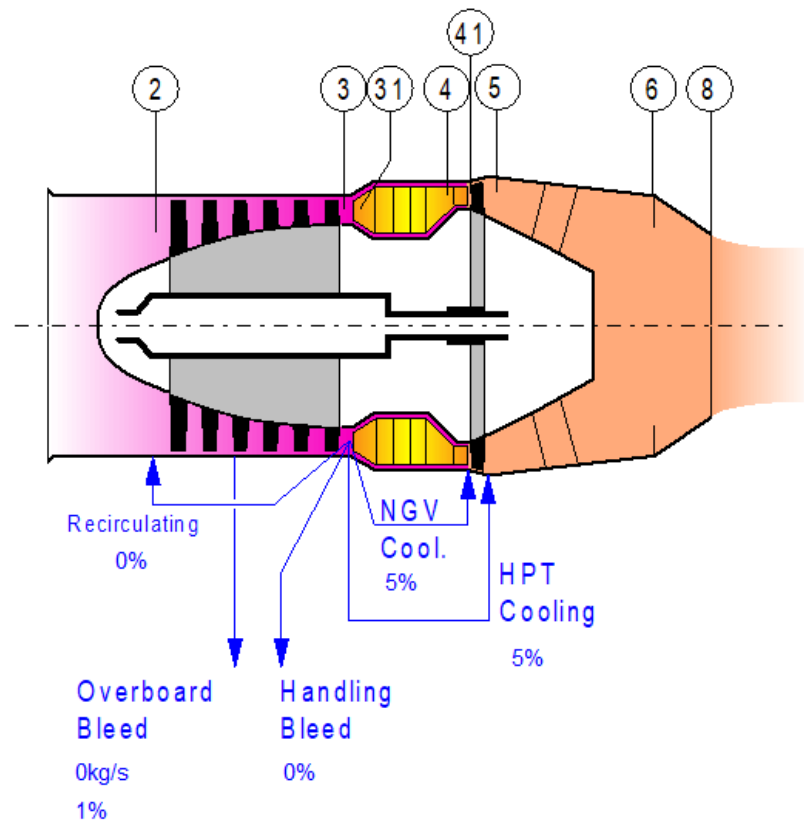


Figure 56. JetCat air system outputs (generic/propane)

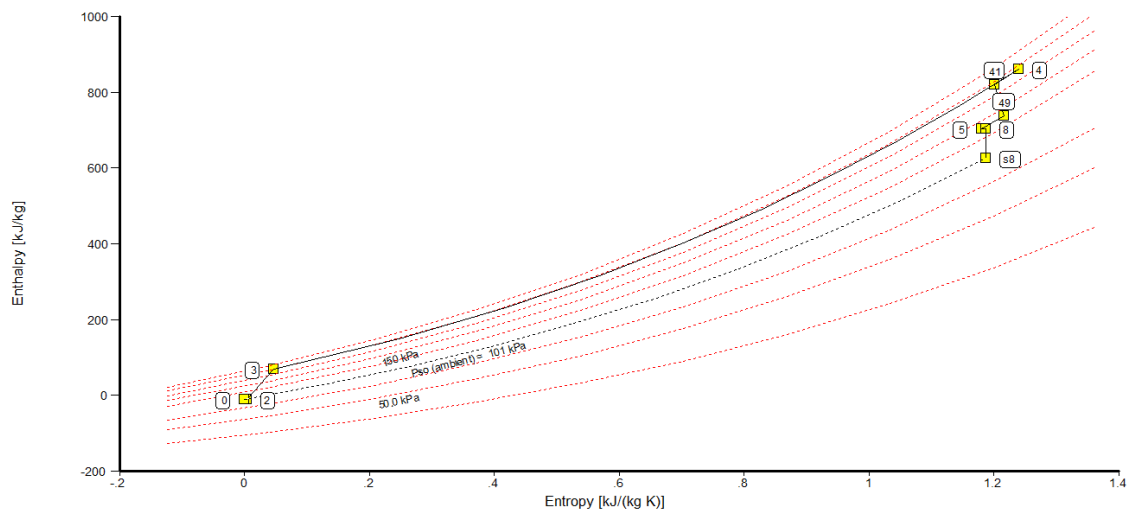


Figure 57. JetCat enthalpy-entropy diagram (generic/propane)

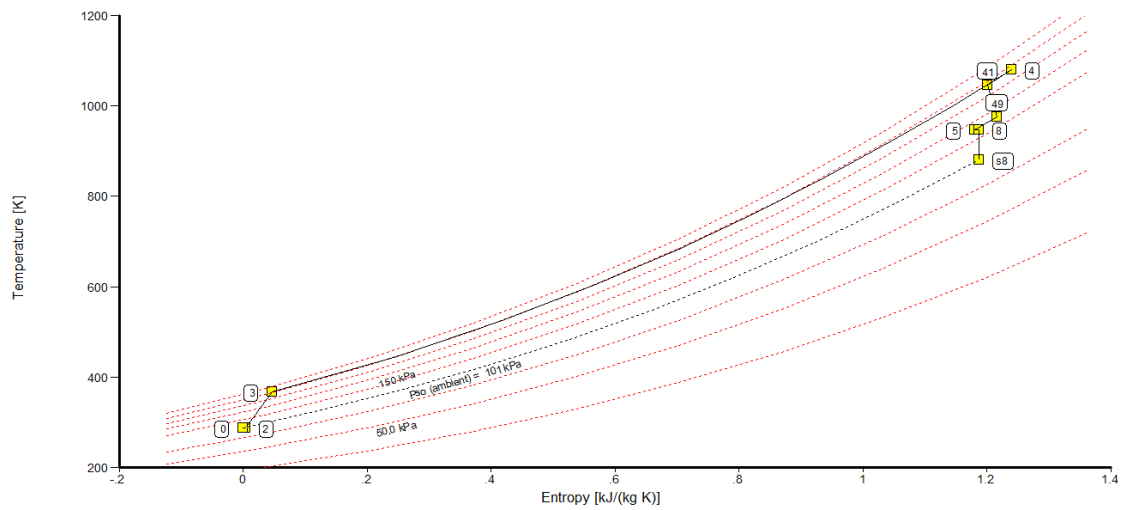


Figure 58. JetCat temperature-entropy diagram (generic/propane)

C. HYDROGEN INPUTS

Tip Clear.		Reheat		Nozzle Selection		Nozzle Calculation	
Basic Data		Air System		Comp Efficiency		Comp Design	
Turb Efficiency							
<div> <div>✚ Flight</div> <div>✚ Testbed</div> </div>							
Altitude				m	0		
Delta T from ISA				K	0		
Relative Humidity [%]					0		
Mach Number					0		
Inlet Corr. Flow W2Rstd				kg/s	0.16		
Intake Pressure Ratio					0.99		
Pressure Ratio					2		
Burner Exit Temperature				K	1080		
Burner Design Efficiency					0.9999		
Burner Partload Constant					1.6		
Fuel Heating Value				MJ/kg	118.429		
Overboard Bleed				kg/s	0		
Power Offtake				kW	0		
Mechanical Efficiency					0.9999		
Burner Pressure Ratio					0.97		
Turbine Exit Duct Press Ratio					0.98		

Fuel: Hydrogen

Figure 59. JetCat basic data (hydrogen)

Basic Data		Air System		Comp Efficiency		Comp Design	
Turb Efficiency							
Tip Clear.		Reheat		Nozzle Selection		Nozzle Calculation	
<div> <div>✚ The Options:</div> <div> <div><input checked="" type="radio"/> 1: Convergent Nozzle</div> <div><input type="radio"/> 2: Con/Di Nozzle</div> </div> </div>							

Fuel: Hydrogen

Figure 60. JetCat nozzle selection (hydrogen)

Tip Clear.		Reheat		Nozzle Selection		Nozzle Calculation	
Basic Data		Air System		Comp Efficiency		Comp Design	
						Turb Efficiency	
Rel. Handling Bleed						0	
Rel. Enthalpy of Handling Bleed						1	
Rel. Overboard Bleed W Bld/W2						0.01	
Rel. Enthalpy of Overb. Bleed						1	
Recirculating Bleed W reci/W2						Off Design Input Only	
Rel. Enthalpy of Recirc Bleed						1	
NGV Cooling Air W CI/NGV/W2						0.05	
Rotor Cooling Air W CI/W2						0.05	
Cooling Air Pumping Diameter				m		0	

Fuel: Hydrogen

Figure 61. JetCat air system (hydrogen)

Basic Data		Air System		Comp Efficiency		Comp Design		Turb Efficiency	
Tip Clear.		Reheat		Nozzle Selection		Nozzle Calculation			
The Options: <div style="display: flex; flex-direction: column; gap: 10px;"> <div><input checked="" type="radio"/> 1: no Reheat</div> <div><input type="radio"/> 2: Standard Reheat Calc</div> <div><input type="radio"/> 3: Special Reheat Calc</div> </div>									

Fuel: Hydrogen

Figure 62. JetCat reheat (hydrogen)

Tip Clear.	Reheat	Nozzle Selection	Nozzle Calculation	Fuel:
Basic Data	Air System	Comp Efficiency	Comp Design	Turb Efficiency

The Options:

☒ 1: no

☐ 2: yes

Nominal Spool Speed | 14000

Figure 63. JetCat compressor design (hydrogen)

Tip Clear.	Reheat	Nozzle Selection	Nozzle Calculation	Fuel:
Basic Data	Air System	Comp Efficiency	Comp Design	Turb Efficiency

The Options:

☒ 1: isentropic

☐ 2: polytropic

☐ 3: calculate it

Isentr.Compr.Efficiency | 0.8

Figure 64. JetCat compressor efficiency (hydrogen)

Tip Clear.	Reheat	Nozzle Selection	Nozzle Calculation	Fuel:
Basic Data	Air System	Comp Efficiency	Comp Design	Turb Efficiency

The Options:

☒ 1: isentropic

☐ 2: polytropic

☐ 3: calculate it

Isentr.Turbine Efficiency | 0.85

Figure 65. JetCat turbine efficiency (hydrogen)

D. HYROGEN OUTPUTS

Summary		Air System					
Station	W kg/s	T K	P kPa	WRstd kg/s			
amb		288.15	101.325		FN	=	0.06 kN
1	0.158	288.15	101.325		TSFC	=	15.1266 g/(kN*s)
2	0.158	288.15	100.312	0.160	FN/W2	=	406.04 m/s
3	0.158	366.81	200.624	0.090	Prop Eff	=	0.0000
31	0.141	366.81	200.624		eta core	=	0.1210
4	0.142	1080.00	194.605	0.146			
41	0.150	1046.64	194.605	0.151	WF	=	9.7289E-4 kg/s
49	0.150	977.57	140.193		s NOx	=	0.03606
5	0.158	950.14	140.193	0.211	XM8	=	0.6888
6	0.158	950.14	137.389		A8	=	0.0011 m²
8	0.158	950.14	137.389	0.215	P8/Pamb	=	1.3559
Bleed	0.002	366.81	200.624		WBld/W2	=	0.01000
-----					Ang8	=	20.00 °
P2/P1 = 0.9900	P4/P3 = 0.9700	P6/P5	0.9800		CD8	=	0.9185
Efficiencies:	isent	polytr	RNI	P/P	W_NGV/W2	=	0.05000
Compressor	0.8000	0.8184	0.990	2.000	WCL/W2	=	0.05000
Burner	0.9999			0.970	Loading	=	100.00 %
Turbine	0.8500	0.8447	0.422	1.388	e45 th	=	0.83470
-----					far7	=	0.00620
Spool mech Eff	0.9999	Nom Spd	14000 rpm		PWX	=	0.00 kW

hum [%]	war0	FHV	Fuel				
0.0	0.00000	118.429	Hydrogen				

Figure 66. JetCat summary of outputs (hydrogen)

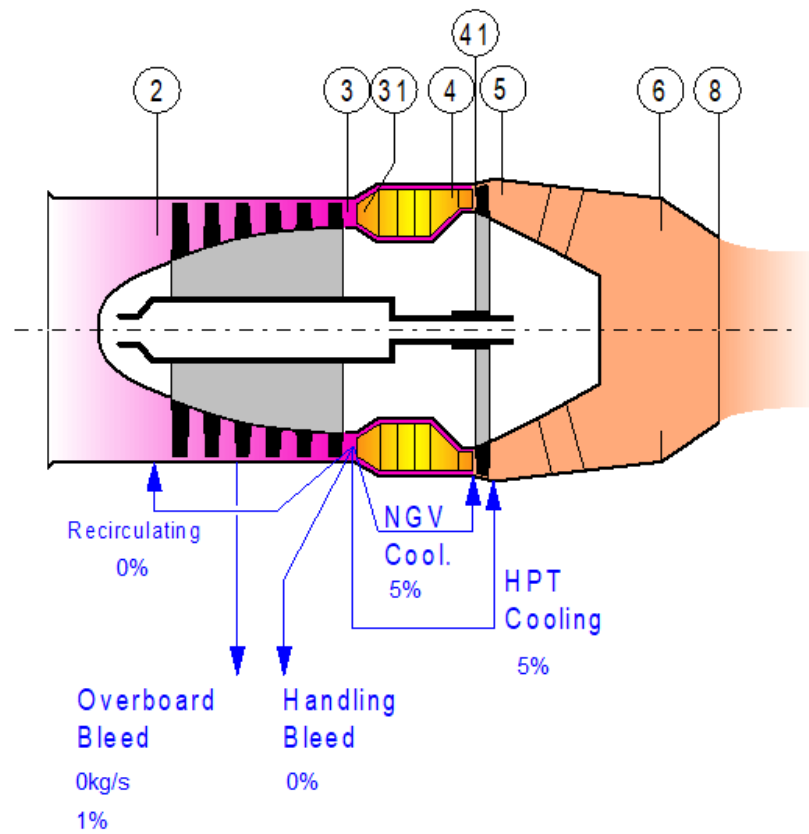


Figure 67. JetCat air system outputs (hydrogen)

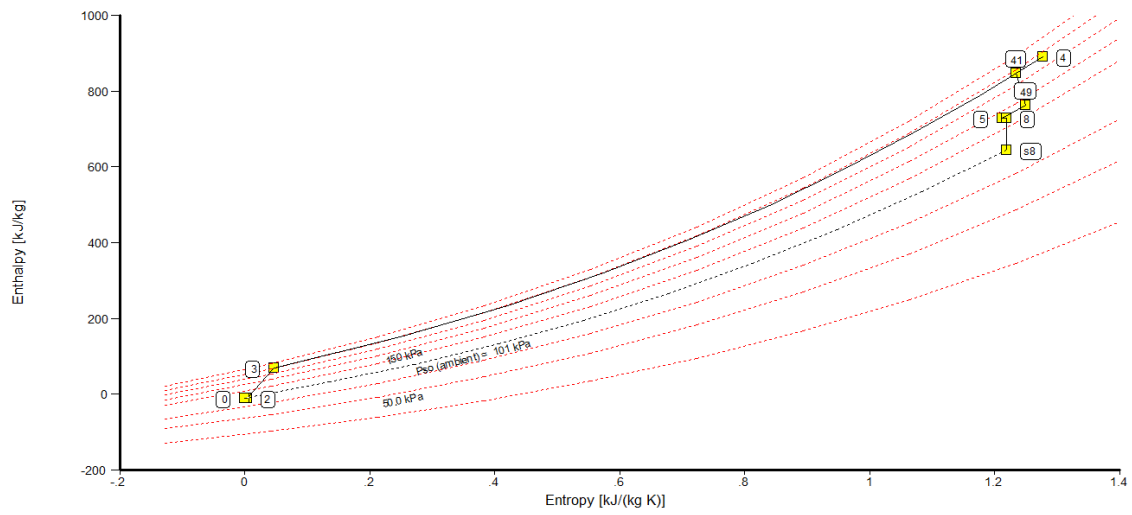


Figure 68. JetCat enthalpy-entropy diagram (hydrogen)

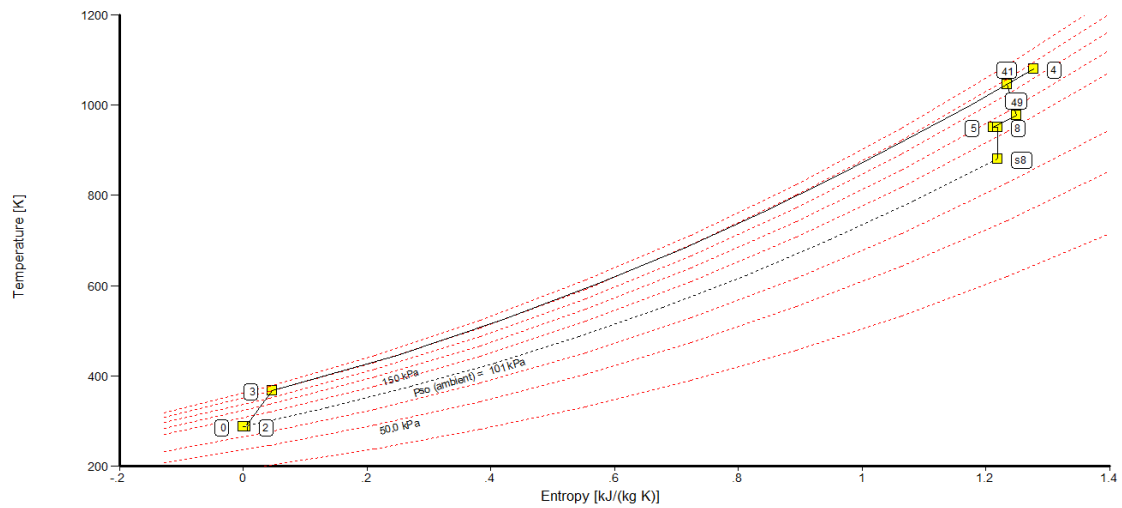


Figure 69. JetCat temperature-entropy diagram (hydrogen)

APPENDIX E. JETCAT BOUNDARY CONDITIONS

The remain boundaries autogenerate by CFX are adiabatic, no slip wall, smooth wall conditions. Ensure the autogenerated boundaries are the desired conditions and that no additional fluid-fluid interfaces were generated when slicing the two solid models.

Table 6. JetCat default domain setup

Domain - Default Domain	
Type	Fluid
Location	B798
Materials	
Hydrogen Air Mixture	
Fluid Definition	Material Library
Morphology	Continuous Fluid
Settings	
Buoyancy Model	Non Buoyant
Domain Motion	Stationary
Reference Pressure	2.0000e+00 [atm]
Combustion Model	Eddy Dissipation
Eddy Dissipation Model Coefficient B	5.0000e-01
Maximum Flame Temperature	2.4000e+03 [K]
Component	H2
Option	Automatic
Component	H2O
Option	Automatic
Component	N2
Option	Constraint
Component	O2
Option	Automatic
Heat Transfer Model	Total Energy
Include Viscous Work Term	True
Turbulence Model	k epsilon
Turbulent Wall Functions	Scalable
High Speed Model	Off
Domain Interface - Trans1	
Boundary List1	Trans1 Side 1
Boundary List2	Trans1 Side 2
Interface Type	Fluid Fluid
Settings	
Interface Models	Rotational Periodicity
Axis Definition	Coordinate Axis
Rotation Axis	Coord 0.2
Mesh Connection	Automatic

Table 7. JetCat inlet boundary conditions

Boundary - Inlet	
Type	INLET
Location	Inlet
Settings	
Component	H2
Mass Fraction	0.0000e+00
Option	Mass Fraction
Component	H2O
Mass Fraction	0.0000e+00
Option	Mass Fraction
Component	O2
Mass Fraction	2.3200e-01
Option	Mass Fraction
Flow Direction	Normal to Boundary Condition
Flow Regime	Subsonic
Heat Transfer	Static Temperature
Static Temperature	3.0000e+02 [K]
Mass And Momentum	Mass Flow Rate
Mass Flow Rate	2.6600e-02 [kg s ⁻¹]
Mass Flow Rate Area	As Specified
Turbulence	Medium Intensity and Eddy Viscosity Ratio

Table 8. JetCat fuel inlet boundary conditions

Boundary - Fuelin	
Type	INLET
Location	Fuelin
Settings	
Component	H2
Mass Fraction	1.0000e+00
Option	Mass Fraction
Component	H2O
Mass Fraction	0.0000e+00
Option	Mass Fraction
Component	O2
Mass Fraction	0.0000e+00
Option	Mass Fraction
Flow Direction	Normal to Boundary Condition
Flow Regime	Subsonic
Heat Transfer	Static Temperature
Static Temperature	3.0000e+02 [K]
Mass And Momentum	Mass Flow Rate
Mass Flow Rate	1.6200e-04 [kg s ⁻¹]
Mass Flow Rate Area	As Specified
Turbulence	Medium Intensity and Eddy Viscosity Ratio

Table 9. JetCat outlet boundary conditions

Boundary - Outlet	
Type	OUTLET
Location	Outlet
Settings	
Flow Regime	Subsonic
Mass And Momentum	Average Static Pressure
Pressure Profile Blend	5.0000e-02
Relative Pressure	-6.0000e-02 [atm]
Pressure Averaging	Average Over Whole Outlet

Table 10. JetCat domain interface boundary conditions

Boundary - Trans1 Side 1	
Type	INTERFACE
Location	Sym1
Settings	
Component	H2
Option	Conservative Interface Flux
Component	H2O
Option	Conservative Interface Flux
Component	O2
Option	Conservative Interface Flux
Heat Transfer	Conservative Interface Flux
Mass And Momentum	Conservative Interface Flux
Turbulence	Conservative Interface Flux
Boundary - Trans1 Side 2	
Type	INTERFACE
Location	Sym2
Settings	
Component	H2
Option	Conservative Interface Flux
Component	H2O
Option	Conservative Interface Flux
Component	O2
Option	Conservative Interface Flux
Heat Transfer	Conservative Interface Flux
Mass And Momentum	Conservative Interface Flux
Turbulence	Conservative Interface Flux

THIS PAGE IS INTENTIONALLY LEFT BLANK

APPENDIX F. JETCAT CFX RESIDUALS

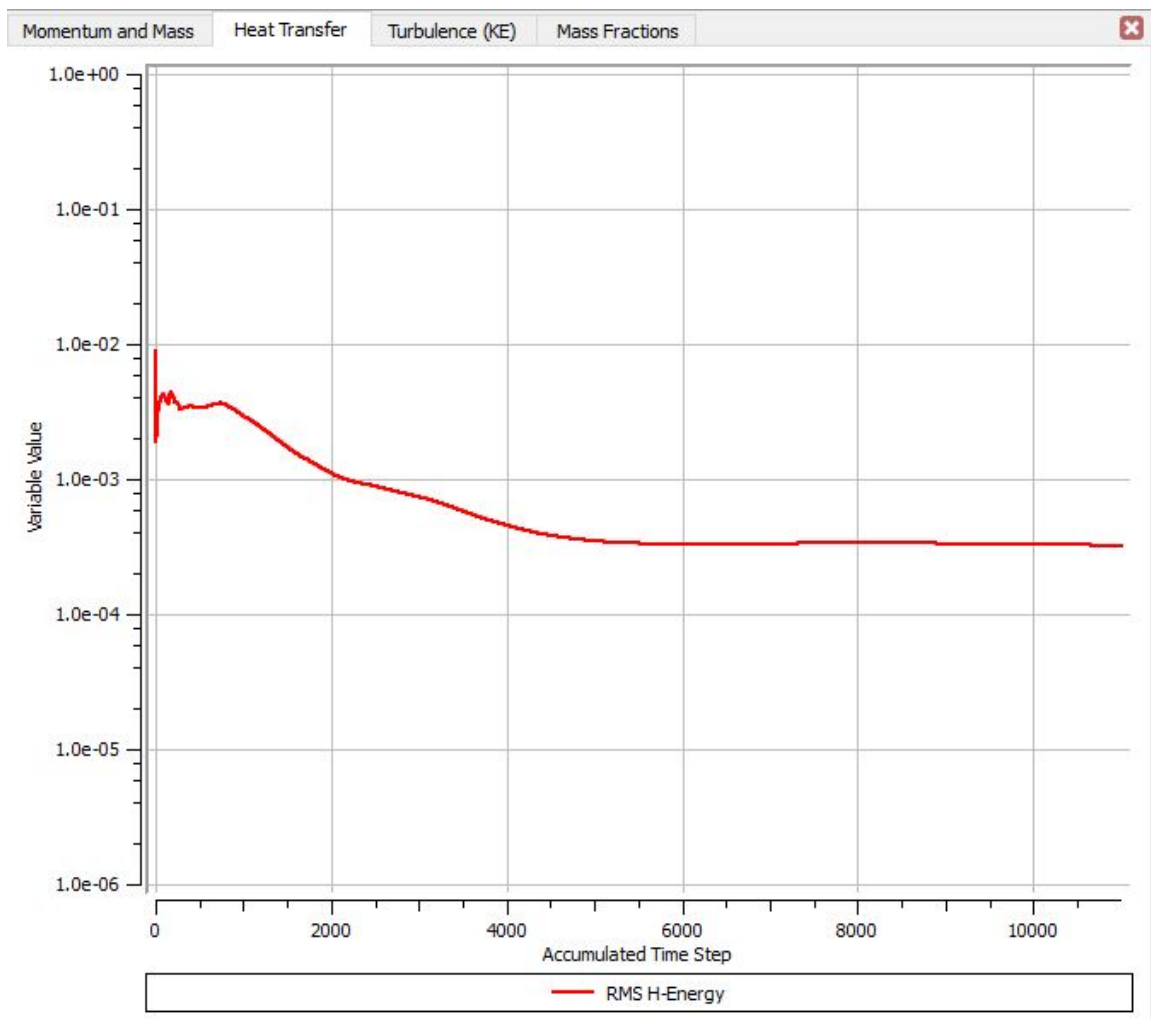


Figure 70. JetCat heat transfer residual

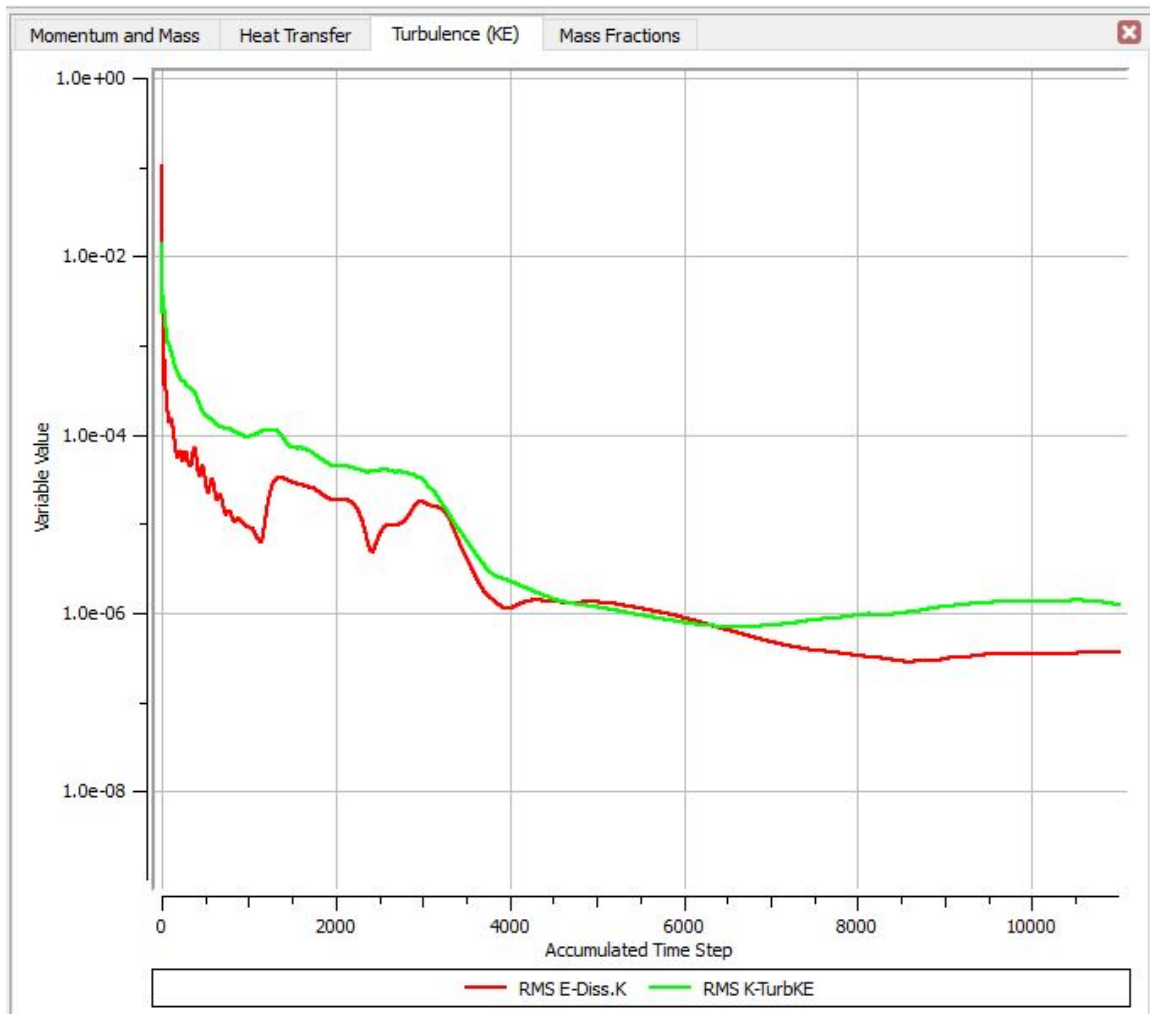


Figure 71. JetCat turbulence residuals

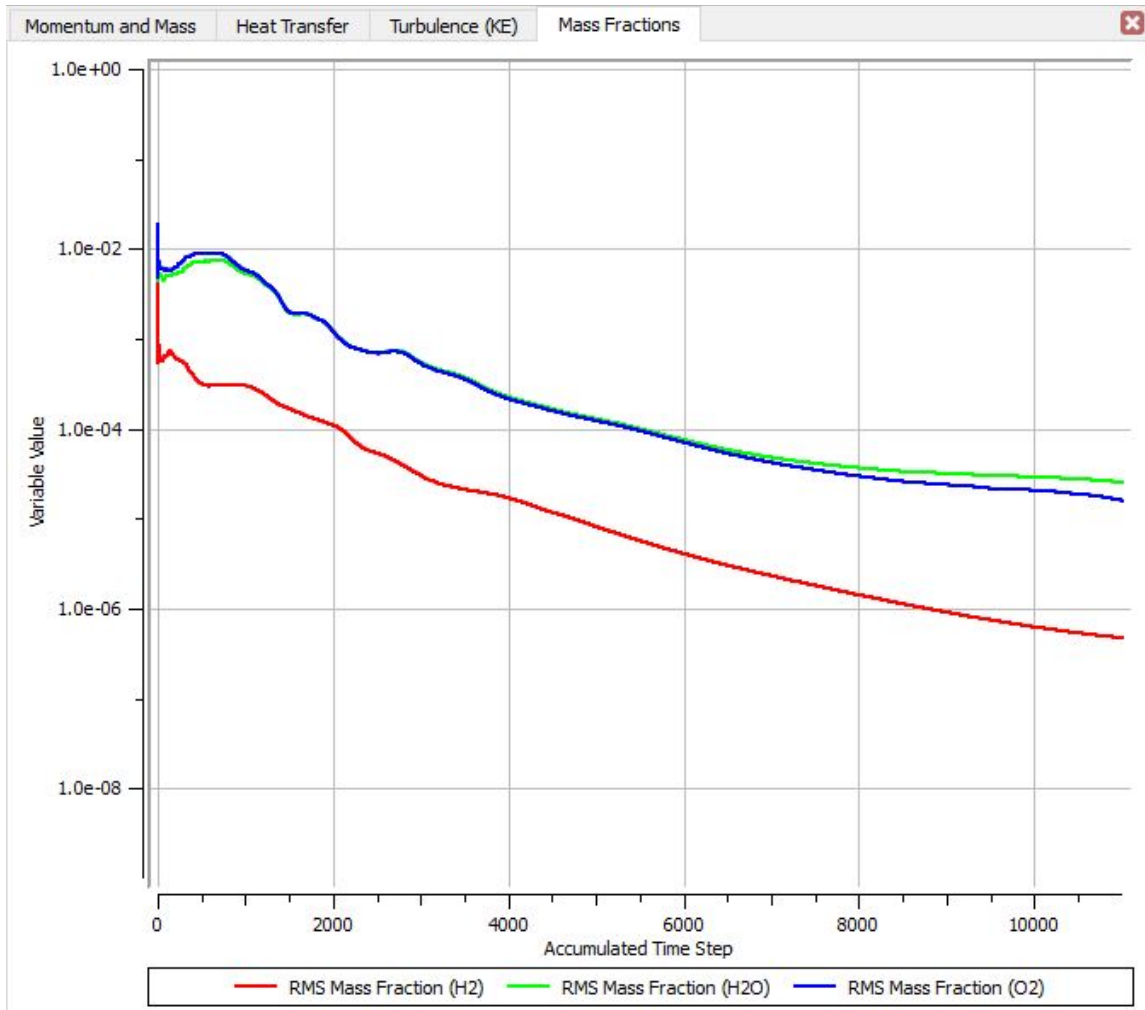


Figure 72. JetCat mass fractions residuals

THIS PAGE IS INTENTIONALLY LEFT BLANK

LIST OF REFERENCES

- [1] Assistant Secretary of the Navy Energy Office, “Department of the Navy: Strategy for Renewable Energy,” Washington, DC, USA, 2012. [Online] Available: <http://www.secnav.navy.mil/eie/Documents/DoNStrategyforRenewableEnergy.pdf>
- [2] Assistant Secretary of the Navy Energy Office, “Department of the Navy: Energy Program for Security and Independence,” Washington, DC, USA, 2010. [Online] Available: <https://www.secnav.navy.mil/eie/Documents/DoNEnergyProgramforSecurityandIndependence.pdf>
- [3] Dr. Jeff Waksman, “Project Pele, Mobile Nuclear Power for Future DoD Needs,” presented at the Naval Postgraduate School, Monterey, CA, USA, Mar. 18, 2021. [Online] Available: <https://nps.edu/web/nps-video-portal/-/project-pele-mobile-nuclear-power-for-future-dod-needs>
- [4] U.S. Department of Energy, “Alternative Fuels Data Center: Hydrogen Production and Distribution.” [Online] Available: https://afdc.energy.gov/fuels/hydrogen_production.html
- [5] K. Mazloomi, and C. Gomes, “Hydrogen as an energy carrier: Prospects and challenges,” Electrical and Electronic Egr. Dept., University of Putra Malaysia, Selangor, Malaysia 2012. [Online] Available: <https://www-sciencedirect-com.libproxy.nps.edu/science/article/pii/S1364032112001220?via%3Dihub>
- [6] B. Kaufmann, “Implementation of a microturbine in a hydrogen energy storage and generation system,” M.S. thesis, Mech. Egr. Dept., Naval Postgraduate School, Monterey, CA, USA 2019. [Online] Available: <https://calhoun.nps.edu/handle/10945/62733>
- [7] R. Hu, private communication, Feb. 2021.
- [8] *X30S-B Load Bank Operation and Service Manual*, Mosebach Manufacturing Company. Pittsburgh, PA, 2017. [Online] Available: <https://mosebachresistors.com/support/manuals>
- [9] Grabcad Community, Santiago. “Combustion Chamber.” February 21, 2014. Accessed October 7, 2020. [Online] Available: <https://grabcad.com/library/combustion-chamber-3>
- [10] *ANSYS CFX Tutorials*, 16th ed. ANSYS, Canonsburg, PA, USA, 2013.
- [11] *400001-001 Rev. C: Capstone MicroTurbine User’s Manual*, Capstone Turbine Corporation, Chatsworth, CA, USA, 2005.

- [12] *410028 Rev D: Stand Alone Operation – Capstone Model C30 and C60/C65*, Capstone Turbine Corporation, Chatsworth, CA, USA, 2006.
- [13] *410013 Rev U: Capstone Remote Monitoring System (User Edition)*, Capstone Turbine Corporation, Chatsworth, CA, USA, 2017.

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
Ft. Belvoir, Virginia
2. Dudley Knox Library
Naval Postgraduate School
Monterey, California